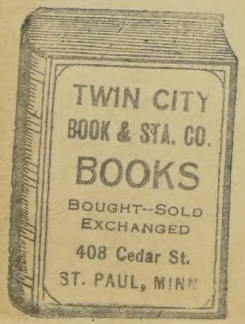
MODERN PHYSICS

CHARLES E. DULL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See page 490.

MODERN PHYSICS

BY

CHARLES E. DULL

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NEWARK, N. J.

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PREFACE

MANY decades ago natural philosophy or physics was studied because men had a desire to know and understand natural laws and phenomena. In the present scientific age, that person who does not acquire a knowledge of the essentials of physics will find himself embarrassed and handicapped as he faces his daily problems. If we judge by the "seven cardinal points," as presented by the Committee for the Reorganization of Secondary Education, no subject in the secondary school course more adequately meets these ideal objectives.

Few subjects touch the student's life more closely than elementary physics. No subject is better fitted to develop the reasoning powers, or to cultivate that uncommon faculty known as "common sense." From the time the pupil opens the water faucet in the morning until he snaps off the electric light upon retiring, he is constantly applying or observing some of the principles of physics. These principles may be connected with the automobile, the airplane, or television; or they may have to do with the more prosaic wheelbarrows, buck-saws, or garden tools.

In the preparation of this textbook the author has tried to keep in mind the pupil's point of view. The language is simple, and the explanations are full enough to enable beginners to understand even those topics that ordinarily appear difficult. Many thought-provoking questions are included, and the number of problems is so great that few pupils will find time to do them all. At least one problem of each kind is solved or explained as a guide for the pupil. Appendix A contains a list of supplementary problems.

In presenting the various topics, the author has generally used the following plan: (1) some historical reference or

familiar illustration is used to introduce the topic; (2) the principle or fact is then stated and explained in language with which the beginner is familiar; (3) enough practical applications are then used to develop the principle and to show the student how it touches his daily life; (4) the illustrations, which are used in profusion, are so closely linked with the context that they are useful in clarifying the more difficult parts and in enlarging the scope of the subject. In some simple problems—those of coefficient of linear expansion, for example—formulas have been discarded because they look more complicated and seem more difficult than the problems themselves. Thus an effort is made to develop analytical methods of solving problems. The usual formulas are listed in Appendix B for the benefit of those teachers who prefer to use them.

More material is included than the teacher will wish to use. It seems easier for the instructor to omit certain topics than it is to ask pupils to gather the material from other sources. No attempt has been made to use smaller type to indicate less important topics, as pupils generally assume that matter set in such type is to be omitted. Thus the choice of material is left to the discretion of the teacher.

A discussion of the automobile is taken up in the last chapter of this book. If one prefers, he may use this material from time to time during the study of the subject, or he may use the chapter as a review of the whole subject of physics. Some new material has been added, but the transmission system affords an excellent review of gear wheels in mechanics, the radiation system furnishes an excellent example of heat distribution, and the elimination of glaring headlights supplies the illumination engineer with a difficult problem. There are few important principles of physics which are not exemplified in the construction and operation of a modern automobile.

NEWARK, N. J.
January, 1929.

C. E. D.

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Naturally, the most up-to-date information and the best illustrative material pertaining to many topics in physics are in the hands of manufacturing concerns. The author has found them

courteous, and willing to coöperate in educational work. He is especially pleased to acknowledge the courtesy of the following, who have assisted by furnishing illustrative material: Aërmotor Co.; American Telegraph and Telephone Co.; A. Schrader's Son; Bausch & Lomb Optical Co.; Bendix Brake Co.; Bethlehem Steel Co.; Brown Bros.; Busch-Sulzer Bros.; Cadillac Motor Car Co.; Central Scientific Co.; Chambers Manufacturing Co.; Chicago Apparatus Co.; Chicago Pneumatic Tool Co.; C. G. Conn, Ltd.; Cooper-Hewitt Electric Co.; *Current Science;* Curtiss Aëroplane & Motor Corporation; DeLaval Cream Separator Co.; Delco-Light Co.; Edison Lamp Works; Edison Storage Battery; Electric Boat Corporation; Electric Controller & Manufacturing Co.; Ford Motor Co.; Franklin Automobile Co.; General Electric Co.; General Gas Light Co.; Goerz Optical Co.; Hyatt Roller Bearing Co.; Hoffman Specialty Co.; John O. Powers Co.; L. E. Knott Apparatus Co.; MacBeth-Evans Glass Co.; Manning, Bowman, & Co.; Minneapolis Heat Regulator Co.; National X-Ray Reflector Co.; Niles-Bement Pond Co.; Pennsylvania System; *Popular Science Monthly; Railway and Locomotive Engineering;* Roeder Cowen Service Corporation; Roller-Smith Co.; Servel, Inc.; Simplex Player Action Co.; *Science and Invention;* Sonora Phonograph Co.; Taylor Instrument Co.; The Electric Storage Battery Co.; The Hoover Suction Sweeper Co.; *The Literary Digest;* The Marion Steam Shovel Co.; Newport News Shipbuilding Co.; The North American Co.; The Okonite Co.; The Pathescope Co.; The Pelton Water Wheel Co.; The Power Manufacturing Co.; The Pressure Cooker Co.; Thermoid Rubber Co.; The Studebaker Corporation of America; The Timken Roller Bearing Co.; The Wellman-Seaver-Morgan Co.; Thomas A. Edison, Inc.; Tolhurst Machine Works; United States Weather Bureau; Velodrome, Newark; Virginian Railway Co.; Walker Vehicle Co.; Walter Motor Truck Co.; Western Electric Co.; Westinghouse Electric & Manufacturing Co.; Weston Electrical Instrument Co.; White Star Line; and, Wright Aëronautical Corporation.

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CHAPTER 1

MATTER

A. INTRODUCTORY

Vocabulary

Matter, anything that takes up room.
Energy, capacity for doing work.
Inertia, indisposition of matter to move or stop moving.
Density, weight per unit volume.
Flywheel, a heavy-rimmed wheel attached to the crankshaft of a gas engine or some other machine.
Theory, an explanation of natural phenomena partially verified, but not usually capable of laboratory proof.

1. Why we Study Physics. In the present era, we are so accustomed to modern miracles that we are apt to accept them without question. Men fly through the air at incredible speed; they drive racing cars at more than two hundred miles per hour; they cross the ocean in a few days in palatial ocean liners; or they crawl along beneath the surface of the sea, making real the dream of Jules Verne. In our study of physics we pause to inquire how such things can be possible.

We turn on a switch and electricity lights our home, toasts our bread, washes our clothes or our dishes, fans us in summer, or runs a sewing machine or a vacuum cleaner. We turn to physics in our effort to learn how these appliances operate.

We put gasoline into the tank of an automobile. "How does it get to the engine?" "What is the purpose of the carburetor?" "What makes the engine run?" "What is the purpose of the clutch?" "Why do we have transmis-

sion gears?" To understand the operation of an automobile, one needs a good course in physics.

It is of interest to inquire how the energy from burning coal is used to run a locomotive or a steamboat, to produce electricity, or to heat a house. To make musical instruments properly, or to select the correct lights and fixtures for the home, one needs a knowledge of physics. It is the province of physics to answer the questions, "Why," "How," and "What" that are constantly arising.

This science also deals with measurement. While quantitative work is usually not so fascinating as the study of causes and effects, yet a few illustrations will suffice to show its importance. A canoe displaces only a few cu. ft. of water, hence it is apt to sink if more than three or four persons enter it; a large steamship displaces thousands of tons of water, and it can carry safely thousands of people. (See Fig. 1.) If one buys a car, the expressions "miles per hour," "miles per gallon," "length of wheel-base," "number of cylinders," and "horse power" all emphasize the importance of arithmetic. Meters are used everywhere to ascertain how much gas, electricity, or water a consumer is using.

In each of the subdivisions of physics—*mechanics*, *heat*, *sound*, *light*, and *electricity*—the questions for which we seek answers are, "What does it do?" "How does it work?" And since these answers will affect our safety and what we can afford to pay, we ask—"How much can it do?" and "What will it cost?"

2. What Is Physics? *Physics is often defined as the science which treats of matter and energy.* This definition does not exclude all the other sciences, since they also deal with matter and energy. Since energy is the capacity for doing work, we find that heat, light, and electrical energy all play important parts in such other sciences as astronomy, chemistry, and geology. *Physics has also been defined as that branch of science which deals with the physical changes in*

FIG. 1. — Physics is a science that deals with air, land, and water.

matter, of which the freezing and evaporating of water, the breaking of wood or glass, and the magnetizing of iron are examples.

3. What Is Matter? Anything that occupies space or takes up room is called *matter.* Wood, iron, water, copper, and salt are all examples of ordinary matter. The student is sometimes astonished to learn that air and other gases are matter. As a tire flattens after a puncture, it becomes quite obvious that the escaping air must have occupied space. Heat and light are forms of *energy;* they do not take up room or have weight.

4. Structure of Matter. Theoretically a piece of marble may be broken into two pieces, those two into four, and so on to infinity. In reality, no kind of matter can be subdivided beyond a certain point without losing its identity. Water may be split up into two gases, but when this happens it loses its characteristic properties. The smallest particle into which matter can be subdivided without destroying its *characteristic* properties is called a *molecule.*

No one has ever seen a molecule; these particles are so small that the best microscope fails to reveal them. Suppose a drop of water were magnified until its diameter equaled that of the earth; if its molecules at the same time were correspondingly increased, it is estimated they would appear about the size of baseballs. By indirect methods it has been learned that one liter (a trifle more than a liquid quart) of air contains 27×10^{21} molecules. If the student will write the figure 27 followed by 21 ciphers, he may have a better concept of the minute size of these particles. An adult in deep breathing may inhale about four times that number of molecules at a single inhalation.

When one pumps up an automobile tire to a pressure of 30 lb. per sq. in., he is crowding twice as many molecules into the tire as when deflated. Despite the enormous number of molecules in so small a space, they are not closely

crowded. The space between the molecules of gases is much greater than that occupied by the molecules themselves. With an ordinary compression pump a man can pump several times as much air into a given space as it contains normally.

The molecule is made up of *atoms*. In the science of physics the *molecule* is the unit of matter, but in chemistry the unit of matter is the *atom*. In the laboratory the chemist builds up new molecules from atoms, breaks up molecules into atoms, or rearranges the atoms in the molecule. By means of the X-ray, scientists have studied the arrangement of the atoms in certain molecules. (See Fig. 2.)

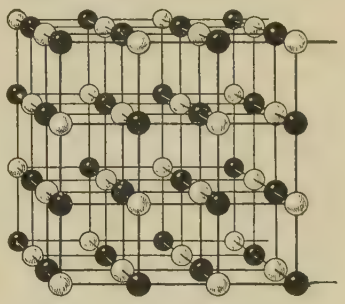

FIG. 2. — Structure of the molecule of common table salt.

Until about the beginning of the twentieth century, scientists believed the atom to be the smallest particle of matter—incapable of subdivision. Since the discovery of the X-ray and the isolation of radium, chemists and physicists are quite certain that the atom is not a simple unit, but quite complex. The atom has a nucleus made up of positively charged particles called *protons*. Some negatively charged particles are also present in the nucleus, but there is always an excess of protons. Surrounding the nucleus and probably revolving around it in a manner similar to the revolution of the planets around the sun, there are extremely small particles, each carrying a charge of negative electricity. These particles are called *electrons*. The hydrogen atom is the lightest atom known, but the electron is only about $\frac{1}{1840}$ as heavy as the hydrogen atom.

5. States of Matter. Everyone knows that matter exists in three states: *solids, liquids,* and *gases*. Solids have a definite

volume and a definite shape; liquids have a definite volume, but they take the shape of the containing vessel; gases have neither a definite volume nor a definite shape. Gases not only take the shape of the containing vessel, but they expand and fill the vessel, no matter what its volume. In solids the molecules cling quite firmly together and do not change their relative positions readily; hence solids have a definite shape. In liquids the attraction between the molecules is less, and they slide over one another quite readily. For this reason liquids change their shape unless they have lateral support. In gases the molecules move so freely that they tend to separate; hence the indefinite expansion.

It is rather difficult to classify a substance like sealing wax, which breaks when struck a sharp blow, but flows under pressure. Both liquids and gases flow freely; hence both are called *fluids*, from the Latin word *fluere*, which means *to flow*. A liquid that flows easily is said to be *mobile;* such a substance as tar, which flows slowly, is said to be *viscous*.

Since heat causes the molecules to move more rapidly, an increase in temperature promotes fluidity. Motor oils that are quite viscous in cold weather become quite mobile in summer. In fact, an increase in temperature may convert a solid first into a liquid, and then into a gas or vapor. Water readily changes to ice, a brittle solid, if cooled to 32° F.; when its temperature is increased to 212° F., water is converted into steam, which is a gas or vapor.

6. Changes in Matter. Many changes are constantly taking place in matter. Wood burns; water freezes; salt dissolves in water; milk sours. These are merely examples of hundreds of changes occurring daily. Changes in matter are of two kinds, *physical* and *chemical*. If the identity of a substance is not lost, the change is *physical;* if a new substance with new characteristic properties is formed, the change is *chemical*. When milk sours, it loses the characteris-

tic properties of sweet milk. Such a change is chemical. The burning of wood is also a chemical change. When water freezes, its molecule is not broken up or rearranged. An increase in temperature converts it to its former state. Such a change is physical. *Physics* deals with *physical* changes in matter; *chemistry* deals with *chemical* changes.

7. Matter Is Indestructible. If we weigh a block of ice, melt it, and weigh the water which is formed, we find that there is no change in weight. *No matter has been lost.* The chemist may let a piece of iron rust, and then recover the iron from the rust. It will have the same weight as the original piece of iron. We may change the form of matter or change its state, but we cannot destroy it. While we cannot destroy matter by means of either a physical or a chemical change, neither can we create matter. Hence the total quantity of matter in the universe is the same today as yesterday. The fact that matter cannot be created or destroyed is usually called the *law of the conservation of matter.*

8. Properties of Matter. Steel is hard; hence it makes good cutting tools. Aluminum transmits heat readily; hence it is suitable for cooking utensils. Different substances have different properties. Some properties, weight and volume, for example, are common to all substances. They are spoken of as *general* properties. There are also many *special* properties which are common to certain substances only. We identify substances by studying their special properties. The use to which a substance is put depends upon its special properties. Since steel is hard and can be tempered, while tin is soft, we make knife blades of steel instead of tin.

B. GENERAL PROPERTIES OF MATTER

9. Volume. If matter occupies space, it must have length, breadth, and thickness. In other words, matter has volume. When we studied arithmetic, we learned how to find the

volume of rectangular solids *directly* by obtaining the product of their length, breadth, and thickness. By the use of an *indirect* method in the laboratory, we shall learn how to find the volume of any solid, no matter how irregular it may be. Liquids and gases also occupy space and have the property of *extension*.

10. Mass and Weight. *The mass of a body is the measure of the quantity of matter it contains.* The mass of a body does not vary.

The weight of a body may vary. It depends upon two factors: (*a*) the mass or quantity of matter it contains; and (*b*) its location on the earth's surface or its distance from the center of the earth. An iron rod contains the same quantity of matter *anywhere* on the earth or 1000 miles above the earth; its *mass* is constant. As its distance from the center of the earth varies, however, the attraction of the earth for it will also vary. *Weight is the measure of the earth's attraction for a body.*

11. Impenetrability. When we pour water into a bottle, the *air* bubbles out with a gurgling sound as the *water* enters. When a nail is driven into a board, it does not penetrate the wood, but it pushes the fibers aside. The same is true in sewing; the needle pushes the fibers of the cloth aside. From these and other examples, we are led to conclude that *no two objects can occupy the same place at the same time.*

FIG. 3. — Matter is impenetrable.

This general property of *impenetrability* makes it possible to find the volume of solids indirectly, no matter how *irregular* they may be. Suppose we put a little water in a graduated cylinder, as in Fig. 3, and note the mark to which the water rises. If we then sink a solid in the water, the water will rise, since both cannot occupy the same space at the same time. The *difference* between the two graduation

marks indicates the volume of liquid displaced. The volume of the liquid displaced is just equal to the volume of the solid. Any non-porous, insoluble solid displaces its *own volume* of water when submerged.

12. Porosity. All matter is more or less porous. The large pores of the sponge cannot escape detection. The pores of an unglazed brick are not so obvious, but water readily finds its way through the brick. Cistern water is often filtered through brick. Iron and silver have still smaller pores, but water under enormous pressure can be forced through even these. When given quantities of alcohol and water are shaken together the combined volume decreases slightly, due to the porous nature of these liquids. Some of the alcohol molecules occupy the spaces between the water molecules, and vice versa.

13. Inertia. A street car cannot stop without the application of some force; neither can it begin to move unless some force is applied to start it. We are all too familiar with the sudden lurch with which we are thrown forward when a car stops suddenly or are jerked backward when the car starts quickly. Matter has no ability in itself to move or to stop moving. Matter is *inert*, which means it is lazy or inactive. On account of the general property of inertia, *bodies in motion tend to remain in motion; bodies at rest tend to remain at rest.* If one leaps from a rapidly moving car, he is likely to fall in the direction the car is going, since his feet are stopped by the friction of the pavement, while inertia impels his body forward. If a car moving at high speed suddenly strikes a tree, the driver is apt to be thrown through the windshield.

Sometimes inertia is put to practical use. The early cars had only a single cylinder and the explosive force of the gasoline drove the car just one-fourth of the time. A heavy flywheel on the crank shaft kept the car moving between working strokes. The band wheel of a sewing machine by

its inertia keeps the machine running during the pauses between the successive pushes upon the treadle. We use inertia in beating or shaking rugs and in shoveling snow or coal. Fig. 4 shows the shallow metal trough from which a

FIG. 4. — The train takes water while traveling at a high speed.

rapidly moving train scoops up water. The inertia of the water forces it up into the tender when the metal scoop is lowered by the fireman.

C. SPECIAL PROPERTIES OF MATTER

14. Tenacity. A cotton thread is more easily broken than a silk thread of the same diameter. Steel wire is stronger than wire made of lead. A body that is not easily pulled apart is said to be *tenacious*. As we ride in an elevator our safety depends upon the *tenacity* of the cable. The tenacity

of any material, or its *tensile strength*, is measured by the force needed to break its unit cross-sectional area. Of the metals, steel has the greatest tensile strength. A bar of high-grade steel one square inch in cross-sectional area can sustain a load of 300,000 lb. Table 7, Appendix C, gives the tensile strengths of various metals.

The cables of the Brooklyn Bridge are over 15 in. in diameter. These cables sustain the weight of the bridge and its load. (See Fig. 5.) The Hell Gate Bridge over the East

FIG. 5. — The Brooklyn Bridge, which is over 1 mile long and 85 ft. wide, is supported by four cables. Each cable is made up of 6300 steel wires, No. 7 gauge. These wires are wrapped in a solid cylinder over 15 in. in diameter. Each cable has a tensile strength of 12,000 tons.

River also serves to illustrate the strength of steel. (See Fig. 6.) If a load is held for a considerable time, the tenacity of the wire is somewhat diminished; hence a wire eventually may be broken by a load which it held safely at first. Engineers call this the *fatigue* of metals.

15. Ductility. If one end of a copper rod is pointed so it will pass through a tapering hole in a steel plate, or die, the

whole rod can be pulled or drawn through the opening. (See Fig. 7.) Thus the length is increased and the diameter reduced. Such a metal is said to be *ductile*. Gold, silver,

FIG. 6. — Hell Gate Arch Bridge is the longest arch in the world. The span between the towers is 1016 ft. and 10 in. The bridge, which is 95 ft. wide, carries four railroad tracks.

platinum, and iron are examples of ductile metals. Fine wires are often made by drawing them through a diamond die, made by drilling a small hole in a diamond. Tungsten wire for use in making the filaments for electric bulbs is made in this manner. For some purposes the wire is drawn so fine that its diameter is only one-sixth that of an average hair. Platinum is the most ductile of metals; it has been drawn into wires only 0.00003 inch in diameter. Glass is very ductile at a high temperature. Quartz is spun so fine that it is impossible to see the threads with the naked eye.

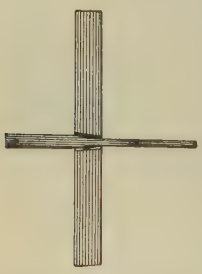

FIG. 7. — Die for drawing wire.

16. Malleability. Iron, copper, lead, aluminum, platinum, and gold may be hammered or rolled into sheets. (See Figs. 8 and 9.) Such metals are said to be *malleable*. Gold is so malleable that it has been beaten into sheets so thin that it would take 250,000 to make a pile one inch high. It would

require about 1000 such sheets to equal in thickness a single leaf of this book. Such thin sheets of metal are translu-

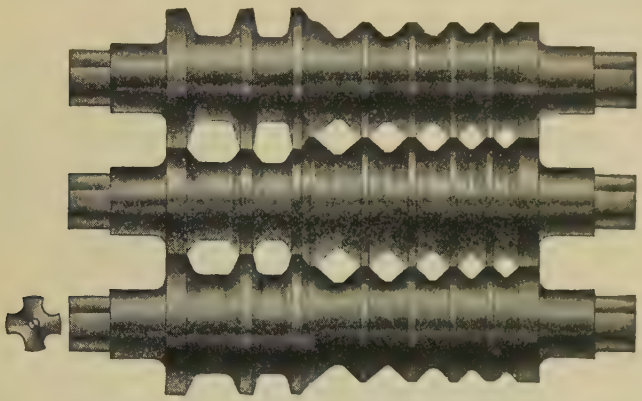

Fig. 8. — Roughing rolls for making bars for shrapnel. (*Courtesy of Scientific American.*)

cent; that is, they transmit some light through them. Fig. 10 shows a press for making steel plates. Some large presses for making armor plate exert a force of 14,000 tons.

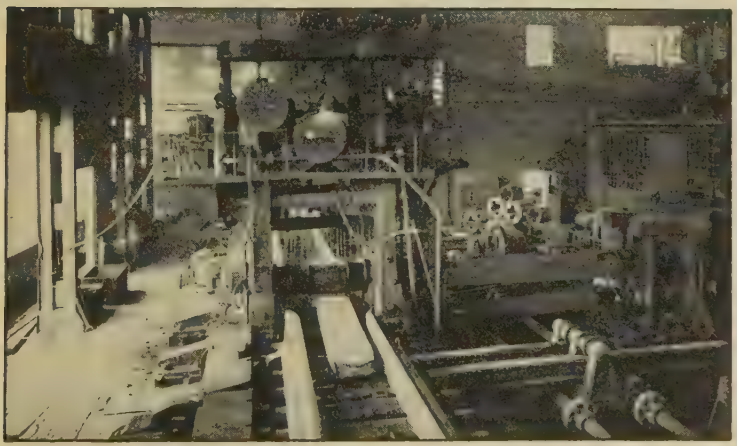

Fig. 9. — White-hot steel passing through the rolls.

17. Hardness. The diamond may be used to cut or scratch glass. Steel will cut tin or copper. We call a substance *hard* if it cannot be easily scratched or abraded. The term *hard* is only a relative one. For example, glass is harder

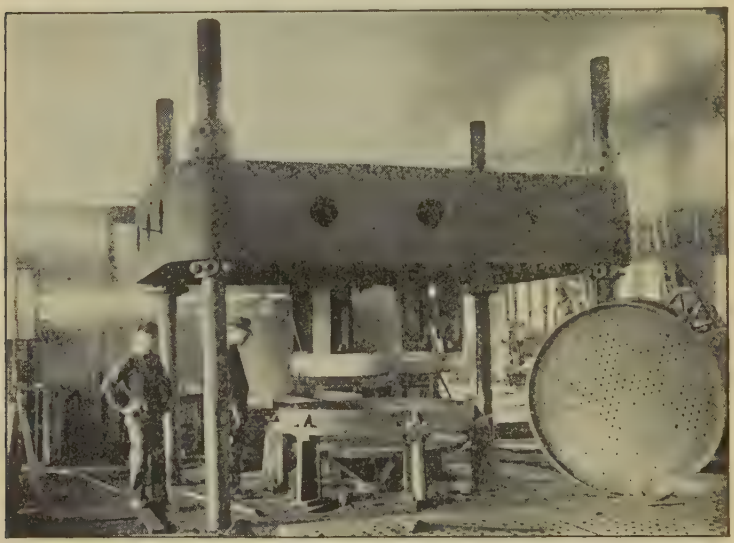

FIG. 10. — 1000-ton flanging press. Hydraulic presses exert a force of a few tons; or, in the case of the very large ones, the force exerted is from 12,000 to 14, 000 tons.

than wood, but it is easily scratched by a diamond. Soapstone, or steatite, is so soft it may be easily scratched with the thumb-nail; it is often pulverized for use in talcum powder. When two substances of unequal hardness are rubbed together, the harder always wears away the softer the more rapidly, unless the soft substance is driven at a high velocity. Hard substances, like sand, emery, carborundum, and diamond dust, are used extensively for cutting, grinding, and polishing.

18. Brittleness. Glass and porcelain break easily when struck a sharp blow. A substance that is easily broken is

said to be *brittle*. Students sometimes confuse hardness and brittleness. Glass is hard and brittle, but steel and some other substances may be hard and tough. Steel is *tempered* to give it the proper degree of hardness; its toughness is increased by heating it and then cooling it slowly. Glassware is cooled slowly to make it less brittle. The process is called *annealing*.

D. MEASUREMENT

19. Two Systems of Measurement. Unfortunately we have two systems of measurement in use in the United States. The student is more or less familiar with the *English system*, but since the tables are easily forgotten, the more important values are given in the appendix for reference.

Practically all civilized countries except Great Britain and the United States use the *Metric system* exclusively. This system originated in France at the time of the French Revolution. It is a decimal system very similar to the table for United States money.

If the Metric system were the only one in use, the whole system of weights and measures could be taught in a few minutes, since there are only three words and a half dozen prefixes to be learned. The *meter* is the unit of length; the *liter* is the unit of capacity; and the *gram* is the unit of weight. The prefixes used for the subdivisions of these units are derived from the Latin: *milli*, $\frac{1}{1000}$; *centi*, $\frac{1}{100}$; *deci*, $\frac{1}{10}$. The prefixes used for the multiples of these units are of Greek derivation: *deca*, 10; *hecto*, 100; and *kilo*, 1000. The only difficult thing about the Metric system arises from the fact that it must sometimes be compared with the more complicated English system.

20. Metric Tables. *Lengths, areas, and volumes.* In the Metric system the units are based upon natural standards. The *meter* is approximately equal to $\frac{1}{10,000,000}$ the distance from the Equator to the Pole. The *standard* meter equals

the distance, measured at 0° C., between two lines scratched on a platinum-iridium bar kept at the archives in Paris. From this original standard thousands of copies have been made and distributed. The table of length in the Metric system is as follows:

10 millimeters (mm.) make 1 centimeter
10 centimeters (cm.) make 1 decimeter
10 decimeters (dm.) make 1 meter
10 meters (m.) make 1 decameter
10 decameters (Dm.) make 1 hectometer
10 hectometers (Hm.) make 1 kilometer (Km.)

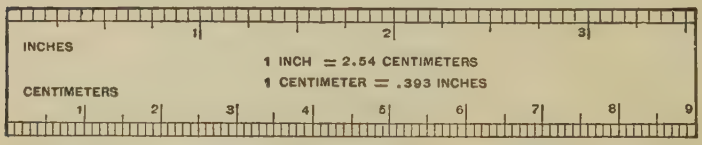

FIG. 11. — Comparison of Metric and English units of length.

The student will have occasion to use the *kilometer*, the *meter*, the *centimeter*, and the *millimeter* quite frequently in his work in physics.

Fig. 11 shows the relation between the Metric and the

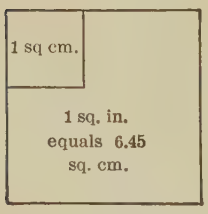

FIG. 12. — Comparison of the Metric and English units of area.

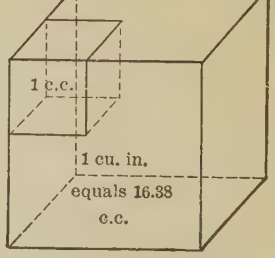

FIG. 13. — Comparison of the Metric and English units of volume.

English units of length. *One inch equals 2.54 cm.* The *meter equals 39.37 inches;* the yard equals $\frac{3600}{3937}$ of a meter.

For measuring surfaces or areas the *square meter* is used. (Fig. 12.) The *cubic meter* is sometimes used for measuring volumes. Vessels used for measuring liquids are often graduated in cubic centimeters (c.c.). The abbreviation $cm.^3$ is often used instead of c.c. Fig. 13 shows the relative sizes of one c.c. and one cu. in.

Capacity. Given a metric ruler, one can easily construct a *liter* measure, since a cubical box 10 cm. on a side holds exactly 1 liter. The liter is equivalent to 1000 c.c., or to 1 cu. dm. The liter is used as the unit of capacity for both dry and liquid measure. It is slightly smaller than our dry quart and a little larger than the liquid quart. The table for capacity differs from the metric table of length only in the substitution of the word "liter" for "meter." Fig 14 shows the relative sizes of the *dry quart*, the *liter*, and the *liquid quart*.

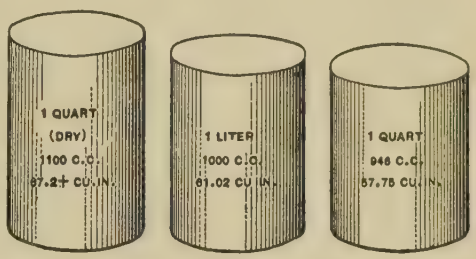

FIG. 14. — Comparison of Metric and English units of capacity.

Weight. The *gram* is the unit of weight in the Metric system, but it is so small that the *kilogram* is more often used. The kilogram (Kgm.) equals 2.2046 lb. A new five-cent piece weighs almost exactly 5 grams. A liter vessel (1000 c.c.) holds just 1 kilogram of water at a temperature of 4° C. Therefore *one cubic centimeter of water weighs one gram.* Sometimes the metric ton (M.T.) is used; it equals 1000 kilograms. Fig.

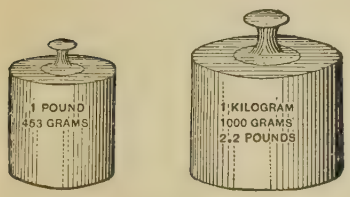

FIG. 15. — Comparison of Metric and English units of weight.

15 shows the comparative size of a pound weight and a kilogram weight.

21. Time. The second is the unit of time in both systems. The Metric system is often known as the *centimeter-gram-second* (C.G.S.) system. The English system is known as the *foot-pound-second* (F.P.S.) system.

E. DENSITY

22. Density. Suppose we have given blocks containing exactly one cu. ft. of each of the following: lead, iron, wood, and cork. If we weigh each one in turn, we find that the weights of *equal* volumes are decidedly different. (See Fig. 16.)

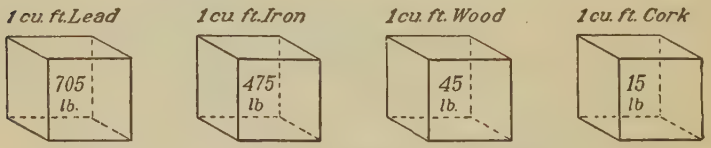

FIG. 16. — The density, or weight per unit volume, varies.

Lead is dense and heavy; cork is exceptionally light. *The weight of unit volume of a substance is called its density.* The unit volume chosen for the English system is usually one cu. ft.; in the Metric system it is one c.c. Hence density is expressed in *lb. per cu. ft.*, or in *gm. per c.c.* To find the density of any substance experimentally we must find its weight; then we determine its volume either by direct measurement, or by the indirect method described in § 11. Then we find its density by dividing its weight by its volume.

Example. A block of wood weighs 180 gm. It is 10 cm. long, 6 cm. wide, and 4 cm. thick. Its volume is 240 c.c (10 cm. $\times$6 cm. $\times$4 cm.). If 240 c.c. weigh 180 gm., then 1 c.c. weighs $\frac{180}{240}$ gm., or 0.75 gm. Therefore the density of the block is 0.75 gm. per c.c.

In solving problems, we may use the letter D to represent

density; W to represent the weight; and V to represent the volume. Then we have the formula,

$$D = \frac{W}{V}, \text{ or } DV = W.$$

Many times we shall have occasion to use the density of water. In *the Metric system the density of water is 1 gm. per c.c.* It is often written, $d = \frac{1 \text{ gm.}}{\text{c.c.}}$, or 1 gm./c.c. In the *English system the density of water* is *62.4 lb. per cu. ft.*, or $d = \frac{62.4 \text{ lb.}}{\text{cu. ft.}}$, or 64 lb./cu. ft. These numbers should be memorized by the student.

Problem. A gold brick is 15 cm. long, 10 cm. wide, and 5 cm. thick. If gold has a density of 19.3 gm./c.c., calculate the weight of the brick.

Solution. The volume is equal to the product of the length, breadth, and thickness. In this case it is 750 c.c. Since weight equals density times volume, then 750×19.3 gm. $= 14{,}475$ gm., the weight.

SUMMARY

Physics is a science which treats of matter and energy. It deals with *physical changes* in matter.

Matter is made up of very small particles called molecules. The molecule, which is the unit in physical changes, is made up of atoms. The atoms in turn contain still smaller particles called electrons. The molecules of matter are always in motion. An increase in temperature accelerates molecular motion.

As the result of a physical change a substance does not lose its characteristic properties; a chemical change causes a substance to lose its identity.

Matter exists in three states: solids, liquids, and gases. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of their container; gases have neither a definite volume nor a definite shape.

Certain properties, such as inertia, impenetrability, extension, weight, and indestructibility are common to all matter. Such special properties as ductility, malleability, tenacity, hardness, and brittleness are peculiar to certain substances.

The student should memorize the following Metric-English equivalents: 1 m. equals 39.37 in.; 1 in. equals 2.54 cm.; 1 Kgm. equals 2.2 lb. Other equivalents are given in the appendix.

The density of a substance is the weight of unit volume of that substance. The student should remember that 1 c.c. of water weighs 1 gm.; also that 1 cu. ft. of water weighs 62.4 lb. For solving problems, the following formula is useful:

$$D = \frac{W}{V}.$$

QUESTIONS

1. Name three physical changes and three chemical changes.

2. Could you find the volume of a lump of sugar by using the indirect method described in § 11? Explain.

3. Show how the property of inertia is exhibited in shoveling coal into a furnace.

4. How do you think heating a cable would affect its tensile strength?

5. Account for the jarring of the water pipes when the water is turned off suddenly.

FIG. 17. — A ball has inertia.

6. How is the principle of inertia utilized in beating or shaking a rug or carpet?

7. Can you see why there would be any objection to the parking of motor trucks on bridges?

8. In Fig. 17 the segment of string supporting the ball is from the same piece as the one attached below. If one pulls at *A* with a quick jerk, the string will break below the weight. If a steady pull is applied, it will break above the weight. Explain.

9. Why does a heavy flywheel cause machinery to run steadily?

10. Why should one face forward when alighting from a car?

11. Explain why shaking or jarring a tree will bring down apples, nuts, etc.

12. What advantages has the Metric system of weights and measures over the English system?

13. Why does it require more force to start a car than to keep it moving?

PROBLEMS

(See Tables 1 and 2 in Appendix C.)

1. Calculate your height in meters; your weight in kilograms.

2. In his flight to Paris, Lindbergh flew 3610 miles at an average speed of about 100 miles per hour. Calculate the distance in kilometers, and his speed in kilometers per hour. 3884.573 — 160.73

3. The Woolworth building is about 790 ft. high. Calculate its height in meters. In centimeters. 240.8 m — 24,078 m.

4. A train runs at a speed of 60 miles per hour. Calculate its speed in ft. per sec. A train runs 90 kilometers per hour. Calculate its speed in m. per sec. 25 —

5. Calculate the value of 1 ft. in cm.; of 1 oz. in gm.

6. How many quarts would a grocer get from a bushel of berries if he measured them with a liquid quart measure? 32 —

7. Compare the weight of 1 lb. of gold with that of 1 lb. of feathers. How much heavier is an oz. of gold than an oz. of feathers?

8. A substance has a density of 7.8 gm. per c.c. Find the weight of a cubical block of this material 3 dm. on a side. 210

9. A tank is 10 ft. long, 8 ft. wide, and 5 ft. deep. How many pounds of water can it hold? 24,96

10. Gold is 19.3 times as dense as water. Calculate the weight of a gold brick 8 in. long, 4 in. wide, and 2 in. thick. Compare this weight with that of an ordinary brick.

11. Lead has a density of 11.3 gm. per c.c. How many c.c. of lead will be needed to make a weight of 50 lb.?

12. A rod 10 ft. long has a diameter of 2 mm. It is drawn through a die which reduces its diameter to 1 mm. How do the cross-sec-

tional area and the length of the new rod compare with the original rod?

13. A manufacturer wishes to make a 500-gm. brass weight. If brass has a density of 8.4 gm./cc., how many c.c. of brass will be needed?

14. A block of ice measures 16″×12″×9″. Calculate its weight in lb., if ice is 0.92 times as dense as water.

15. An iron bar is 5 cm. dia. and
find the weight of the bar in gm.
16. the
is 16 ×
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CHAPTER 2

MECHANICS OF LIQUIDS

A. LIQUID PRESSURE AND TOTAL FORCE

Vocabulary

Calibrate, to graduate an instrument, or to verify its graduation.
Cylinder, a tubular chamber in an engine or other machine.
Piston, a solid cylinder that fits the tubular chamber of an engine, or other machine, gas tight; but it may be driven back and forth by gas, steam, or other pressure.
Hydraulic, pertaining to liquids in motion.
Hydrostatic, pertaining to liquids at rest.
Counterpoise, a weight used to counterbalance another.
Law, a statement of natural processes and phenomena; it is generally capable of laboratory proof.

23. Liquids Exert Pressure. Since water or other liquid flows out of a hole in the side or bottom of a containing vessel, liquids must evidently exert pressure against the sides and bottom of the container. If we push a piece of cork or a block of wood under water, it will rise to the surface again as soon as it is released. Therefore the water must also exert an upward force upon the block. One must use force to *hold* a block of wood or a piece of cork under water. It is the upward force which water exerts that causes boats to float. In the same way, liquids exert an upward thrust or force upon bodies that are dense enough to sink, thus causing such bodies to lose part of their weight when submerged. *We may define force as a push or pull.* Force is usually measured in grams or pounds. When force is applied to *unit area* it is called *pressure.* Therefore we measure pressure in *lb. per sq. in. or sq. ft.*, or in *gm. per sq. cm.*

24. Liquid Pressure Is Proportional to the Depth. Just as a brick lying on a table presses upon the table, so water or any other liquid poured into a vessel exerts force or pressure upon the bottom of the vessel. Such force is due to the weight of the liquid. When several bricks are piled upon one another the downward pressure is increased. Likewise every layer of liquid sustains the weight of the layer directly above it; hence the *pressure of a liquid must increase in direct proportion to the depth.* If the unit area pressed upon is 1 sq. cm., as in Fig. 18, then water 1 cm. deep exerts a pressure of 1 gm., which is the weight of 1 c.c. of water; the pressure at a depth of 2 cm. equals 2 gm.; for each cm. increase in depth the increase in pressure is 1 gm. If the unit area pressed upon is 1 sq. ft., water 1 foot deep exerts a pressure of 62.4 lb. This is also the weight of 1 cu. ft. of water. The student must picture in his imagination that 1 cu. ft. of water 1 foot deep rests upon a base having an area of 1 sq. ft. On each sq. in., the pressure of water is $\frac{1}{144}$ of 62.4 lb., or *0.433 lb. for each foot in depth.*

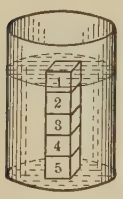


FIG. 18. — Liquid pressure increases with the depth.

25. Liquid Pressure Is Proportional to Density. Liquids vary in density. Mercury is a dense liquid, weighing 13.6 times as much as an equal volume of water. Since the pressure caused by liquids is due to the weight of the liquid, we would expect mercury to exert much greater pressure than water of the same depth. Experiment shows that our reasoning is correct. *The pressure exerted by a liquid is directly proportional to its density.* We have learned that water 10 cm. deep exerts a pressure of 10 gm. Mercury 10 cm. deep exerts a pressure of 136 gm. (10×13.6 gm.). Since gasoline is only about 0.7 as dense as water, the pressure exerted at a depth of 10 cm. in gasoline is only 7 gm. (10×0.7 gm.). Put in the form of an equation,

$$pressure = depth \times density.$$

Using the letter p to represent pressure, h for depth, and d for density, the equation becomes

$$p = hd.$$

PROBLEM. A diver goes down to a depth of 150 ft. in sea-water; density equals 64 lb./cu. ft. Calculate the pressure on each sq. ft. of his body. Calculate the pressure on each sq. in. of his body.

Solution. The depth h is given as 150 ft.; and the density d, which is 64 lb./cu. ft. The pressure p is required. Substituting these values in the formula, $p = hd$, then $p = 150 \times 64$, or 9600 lb. on each sq. ft. To find the pressure in pounds per sq. in., we divide 9600 lb. by 144, the number of sq. in. in 1 sq. ft. The quotient is 66.7 lb.

PROBLEM. For fighting fire in a certain city, water must be supplied at a pressure of 150 lb. per sq. in. How high must a reservoir be above the city to supply such pressure?

Solution. $P = 150$ lb. per sq. in.; $d = 62.4$ lb./cu. ft.; h is unknown. From the equation,

$$p \text{ (in lb. per sq. in.)} = \frac{h \text{ (in ft.)} \times d \text{ (in lb. per cu. ft.)}}{144}$$

$$150 = \frac{h \times 62.4}{144}$$

Then, $150 \times 144 = h \times 62.4$ Whence, $h = 346.1$ ft.

26. Liquid Pressure Is Independent of Direction. A pile of bricks resting on a table exerts pressure in a *downward* direction only, because they are solid and their molecules do not move over one another freely. The molecules of a liquid, however, move over one another so freely that a liquid takes the shape of its container; therefore we may expect liquids to press outward in a *sidewise* direction. Our study of floating objects convinces us that liquids push *upward* to the surface as well as *downward* and *sidewise*.

To illustrate, we may pour mercury into the three tubes shown in Fig. 19 until it stands at the same height in each, and then lower them all into water so that the open ends are at the same depth. The pressure of the water will cause

the mercury to rise in the long arm of each tube. At *A* the water presses *downward;* at *B* the pressure is *upward;* while at *C* a *sidewise* pressure is exerted. The mercury stands at the same level in the long arm of each tube. As measured by the mercury columns the pressures are all equal. This is one way of showing that *liquid pressure is independent of direction.*

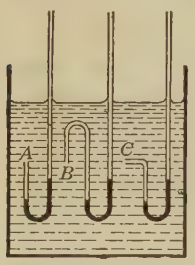


FIG. 19. — Liquid pressure is equal in all directions.

Let us try to picture a drop of water in the center of a glass of water. The pressure upon this drop of water must be *equal in all directions,* or currents would be produced in the water. Since liquid pressure is independent of direction, *it is also independent of the shape of the container.* (See Fig. 20.)

27. Liquid Pressure Is Independent of Shape or Area of Container. Since pressure is measured in terms of unit area, such as lb. per sq. in., or gm. per sq. cm., we need not consider the *total* area in solving problems dealing with liquid pressure. The area of the liquid surface inside a teakettle is much greater than that of the liquid in the spout, but the pressure is the same in both cases. If the pressure increased with the area, water would always flow out of the spout of the teakettle.

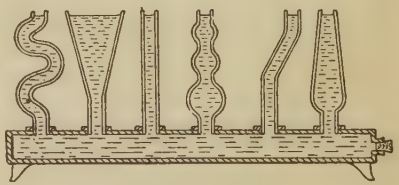


FIG. 20. — Liquids stand at the same height in communicating vessels.

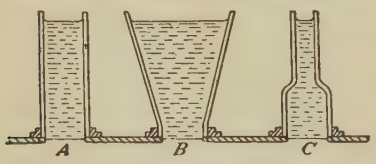


FIG. 21. — Liquid pressure is independent of the area or shape of the container.

From the preceding section, one would infer that liquid pressure is independent of the *shape* of the container. Pascal's vases may be used to

demonstrate this fact. (See Fig. 21.) The area of the diaphragm at the bottom of these vases is the same, and it may be considered as unity. A pointer used to show the increase in pressure as water is poured into these vases indicates the same pressure for all three vases, although their shapes are different and the total amount of water is also different. Liquids stand at the same height in communicating vessels, no matter what their shape. Hence we conclude that *liquid pressure is independent of the shape and area of the container.*

In conclusion, we may summarize the following LAWS OF LIQUID PRESSURE:

1. *Liquid pressure is directly proportional to the depth of the liquid.*

2. *Liquid pressure is directly proportional to the density of the liquid.*

3. *Liquid pressure is independent of the area or shape of the container; it is also independent of direction.*

28. Direct and Inverse Proportion. The terms *direct proportion* and *inverse proportion* are used frequently in stating facts and laws in physics. *Two quantities are directly proportional to each other when an increase or decrease in one of them produces a corresponding increase or decrease in the other.* In the formula derived in section 25, we observe that an *increase* in the depth of a liquid *increases* the pressure, and that an *increase* in the density of the liquid *increases* the pressure.

Two quantities are inversely proportional to each other when an increase in one of them produces a corresponding decrease in the other. If we squeeze a tennis ball, its volume becomes smaller. Suppose we refer to the formula for density,

$$D = \frac{W}{V}.$$

We observe that an *increase* in W without any change in V

causes an *increase* in D; an *increase* in V without any change in W causes a *decrease in* D. Hence, the density of an object is *directly* proportional to its weight and *inversely* proportional to its volume.

Let us plot a graph or curve to show direct proportion, using data obtained by experiment.

Depth of	1 cm.,	pressure equals	1 gm.
Depth of	3 cm.,	pressure equals	3 gm.
Depth of	5 cm.,	pressure equals	5 gm.
Depth of	9 cm.,	pressure equals	9 gm.
Depth of	12 cm.,	pressure equals	12 gm.

Suppose we let O represent the origin of the graph, Fig. 22, and measure off on the line xx' distances equivalent to the various pressures. For convenience let us use one small space to represent one gram. Next let us measure off on the line yy' distances *equivalent* to the depth in cm., using one small space to represent 1 cm. Point a represents a pressure of 1 gm. at a depth of 1 cm.; point b represents a pressure of 3 gm. at a depth of 3 cm. In a similar manner we locate the points c, d, and e, and draw a line from the origin of the curve through all these points. This line, OS, is a curve of *direct proportion.*

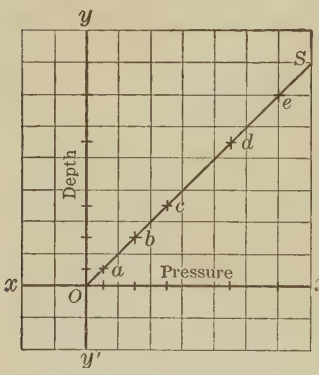


FIG. 22. — Direct proportion curve.

29. Total Force on the Bottom of a Containing Vessel. We have learned that the pressure which a liquid exerts, on the bottom of a containing vessel, for example, equals the product of the depth and the density. While engineers refer to pressure in lb. per *sq. in.*, it will generally be more convenient for us to use the *sq. ft.* as the unit area. On the bottom of a

tank containing water 10 ft. deep, the pressure on each sq. ft. equals depth (10 ft.)×density (62.4 lb. per cu. ft.), or 624 lb. per *sq. ft.* This is equal to 4.33 lb. per *sq. in.*

NOTE. While the following suggestion may not accord with *formal* mathematics, yet it does aid the beginner. Let us write, $d = 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$. As we multiply, 10 ft.$\times 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$, suppose we assume that the denomination *ft.*, which in the numerator represents depth, will change the *cu. ft.* in the denominator to *sq. ft.* By cancellation, $10 \cancel{\text{ft.}} \times 62.4 \frac{\text{lb.}}{\cancel{\text{cu. ft.}}\ (\text{sq. ft.})}$. Whence, pressure = $624 \frac{\text{lb.}}{\text{sq. ft.}}$.

Since pressure is the force acting on *unit area*, to find the *total force* acting on the bottom of a vessel we merely multiply the *area* by the *pressure.* Stated algebraically,

total force = area × pressure, or

total force = area × depth × density.

By using F to represent total force, A for area, h for depth, and d for density, the formula becomes,

$$F = Ahd.$$

PROBLEM. A box 10 ft. long, 8 ft. wide, and 6 ft. deep is full of water. Find the total force on the bottom of the box.

Solution. The area pressed upon is 10 ft.×8 ft., or 80 sq. ft.; the depth of the water is 6 ft., and its density $62.4 \frac{\text{lb.}}{\text{cu. ft.}}$.

total force = area × depth × density.

total force = $80 \times 6 \times 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$ or 29,952 lb.

NOTE. In the foregoing problem, suppose we assume that the *sq. ft.* of the area by *ft.* in depth completely *cancel* the cu. ft. in the denominator as follows: $80 \cancel{\text{sq. ft.}} \times 6 \cancel{\text{ft.}} \times 62.4 \frac{\text{lb.}}{\cancel{\text{cu. ft.}}}$. Therefore, the answer is 29,952 *pounds.*

PROBLEM. Find the total force on the bottom of a box 3 m. long, 2 m. wide, and 1 m. deep, if the box is full of water.

Solution. Changing m. to cm., we have 300 cm. $\times$200 cm. $\times$ 100 cm. The area pressed upon is 300 cm. $\times$200 cm., or 60,000 sq. cm.; the depth is 100 cm.; and the density is 1 $\frac{\text{gm.}}{\text{c.c.}}$.

By substituting in the formula, total force will equal 60,000 $\times 100 \times 1$ $\frac{\text{gm.}}{\text{c.c.}}$ The answer is 6,000,000 gm.

30. Total Force on the Side of a Containing Vessel, or Against a Dam. Everybody knows the story of the Dutch boy at the dike. As he stopped the small hole in the dike, he was resisting the sidewise pressure of the sea. As the soil around our houses fills with water, the sidewise pressure may become great enough to push the water through our cellar walls. In building a dam, engineers must calculate the total force which the water will exert against the side of the dam. We know that in our calculations we must always use for the area the *area of the surface pressed upon.* We know, too, that pressure is independent of direction, but we must consider what depth to use.

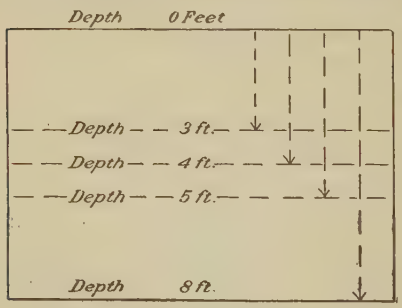


FIG. 23. — Pressure against a vertical surface varies with the depth.

Imagine that the room in which you are sitting is full of water. Its length is 15 ft.; its width is 12 ft.; and its ceiling is 8 ft. high. The area of the longer side of the room is equal to the length, 15 ft., multiplied by the height of the wall, 8 ft. The *area pressed upon* is 120 sq. ft. At the floor the water is 8 ft. deep; at the ceiling the water is 0 ft. deep. From Fig. 23 we see that the depth varies. Halfway up the wall, the water is 4 ft. deep; 3 ft. from the floor, the water is 5 ft. deep; and 3 ft. from the ceiling, the water is 3 ft.

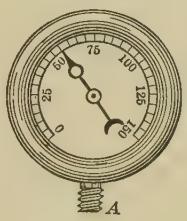
deep. The *average depth* is 4 ft. $\left(\frac{0+3+4+5+8}{5}=4.\right)$ Since the depth of a vertical surface varies, we must use the *average depth*. Then the total force on the wall of the room = 120 sq. ft. (area) $\times$ 4 ft. (average depth) $\times$ 62.4 $\frac{\text{lb.}}{\text{cu. ft.}}$.

The force is equal to 29, 952 lb.

In any case total force equals the area of the surface pressed upon times the average depth times the density. For *horizontal* surfaces the depth is uniform at all points. Hence, $F = Ahd$. For *vertical* surfaces, the average depth is usually equal to *half* the depth. Hence, $F = A\frac{h}{2}d$.

31. How Is Pressure Measured? Occasionally the water pressure in some cities becomes low in dry weather. To be certain that the pressure is great enough to fight fires effectively, a pressure gauge of some kind is used. An *open manometer* is shown in Fig. 24. Here the pressure of the water

FIG. 24.—Open manometer.



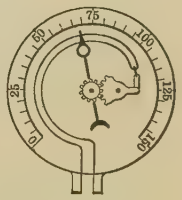


FIG. 25. — Bourdon pressure gauge.

is balanced against a column of mercury. The manometer, which is partially filled with mercury, is attached to the faucet and the water is turned on. The pressure is measured by the height of the mercury column AB. If the tube has a cross-sectional area of 1 sq. in., the weight of the mercury column in pounds equals the pressure of the water in lb.

per sq. in. Sometimes a *closed manometer* is used, but more often water pressure is measured by means of a spring gauge, which is calibrated to read directly in pounds per square inch. (See Fig. 25.) The pressure of the water tends to straighten out the flat, curved tube, which is attached at one end to a lever geared with the pointer.

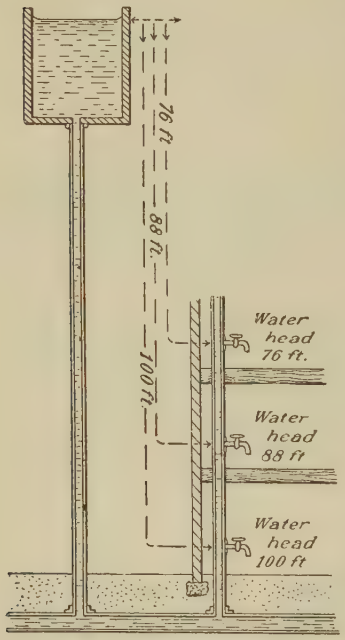


FIG. 26. — Water head is greater at lower floor.

The expression "head of water" or "water head" is in common use by engineers. If the *difference* of levels in communicating pipes is 144 ft., the water head is said to be 144 ft. Such a water head produces a pressure of 62.4 lb. per sq. in. If we refer to Fig. 26, we can understand why the water head on the different floors of the same building is not the same.

32. Applications. (*a*) *Water seeks its level.* Water stands at the same height in communicating vessels, whatever their shape or relative area. The water in the spout of a tea-kettle stands at the same level as the water in the kettle. If we picture the surface of the water in a tank as having momentarily the form shown in Fig. 27, we can understand why water seeks its level. The water heads at *A* and *B* are greater than at *C*. Hence the greater pressure at these points will cause the water to flow in the directions

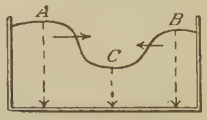


FIG. 27. — Water flows until surface is level.

shown by the arrows until the surface is level. The water-gauge on a steam boiler is another application. (See Fig. 28.) If you have a steam boiler in your basement, the level of the water in the glass gauge shows the level of the water inside the boiler.

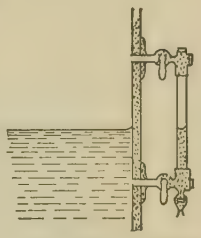


Fig. 28. — Water gauge.

The water supply for some cities is drawn from a reservoir higher than any part of the city itself. Since water seeks its level, it readily rises through the water pipes in the houses to the taps or faucets. If, however, part of a building happens to be higher than the level of the reservoir, the floors above the reservoir will be without water. In such a case a pump must be used to supply the upper floor. Many cities are forced to install pumping stations, since their water supply is lower than the top floors of the high buildings. Fig. 29 is a diagrammatic sketch which shows how water may be

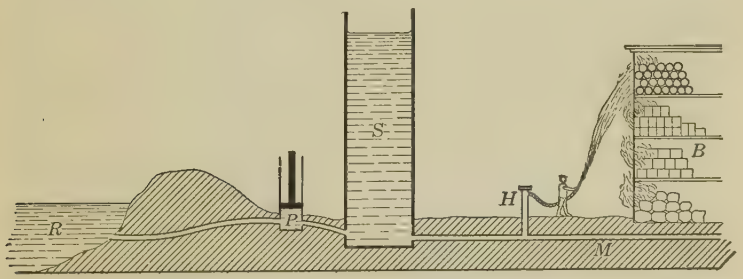


Fig. 29. — City water supply. *R*, reservoir; *P*, pumping station; *S*, standpipe; *H*, hydrant; *M*, water main; *B*, building.

supplied to cities. The pumping station at *P* pumps water from the reservoir *R* to the standpipe *S*, which is higher than any building in the city. The upper floors of tall skyscrapers are generally supplied by independent pumping systems.

The *artesian well* is an illustration of the fact that water seeks its level. In Fig. 30, G is a layer of water-saturated gravel between two strata of impervious rock. When a hole is drilled through the upper stratum, the pressure of the water at A and B forces the water out, thus causing a flowing well at W.

(*b*) *Pressure on submerged bodies.* We have already learned that the pressure on an area of one sq. ft. submerged to a

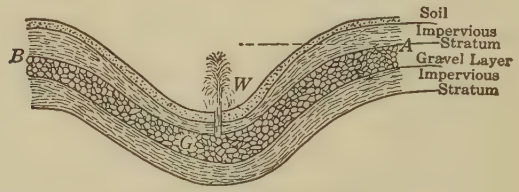


Fig. 30. — Artesian well.

depth of one foot is 62.4 lb. Since the pressure increases with the depth, it is easy to see that the pressure soon becomes enormous as a body is lowered into water. Divers cannot descend in safety to a very great depth, although cases are on record of deep-sea diving to a depth of over 300 ft.

The hull of a vessel must be strong enough to resist the pressure of the water in which it is submerged. This problem becomes a difficult one in constructing submarines.

(*c*) *Total force as related to construction work.* Before building cisterns, tanks, standpipes, dams, and canal locks, the engineer must compute the pressure or the total force to which these structures will be subjected. The amount of material used in constructing dams for storage reservoirs is enormous. Fig. 31 gives an idea of the enormous strength that canal locks must have, to withstand the total force of the water when the gates are closed.

QUESTIONS

1. Explain why water flows down hill.
2. Why is it difficult to keep water out of cellars?
3. Does water flow faster from a tap in the basement than from a similar tap on the third floor? Explain.

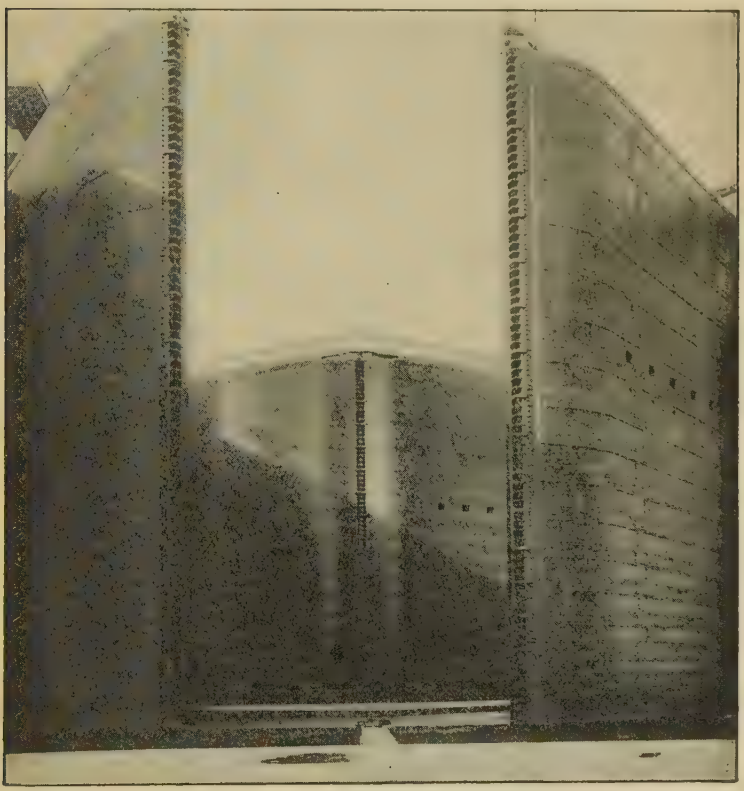


FIG. 31. — The Panama Canal locks are 900 ft. long, 95 ft. wide, and the water has a minimum depth of 41 ft. Enough concrete was used in the construction of each lock to make a pile as big as the Great Pyramids. The steel gates are 7 ft. thick, 65 ft. long, and from 47 to 82 ft. high; their weight is from 300 to 600 tons.

4. Some standpipes are made like that shown in Fig. 32. The other type is shown in Fig. 33. If the water stands at the same height in both, how do the pressures compare?

5. Should a dam be made thicker at the bottom or at the top? Give a reason for your answer.

6. Three Pascal vases are made like those shown in Fig. 21. The area of the base is the same in all three cases. They are filled to

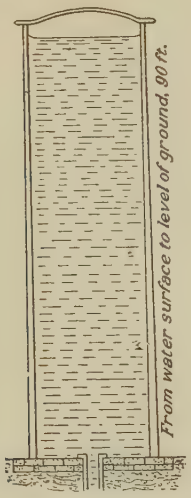


Fig. 32. — Standpipe.

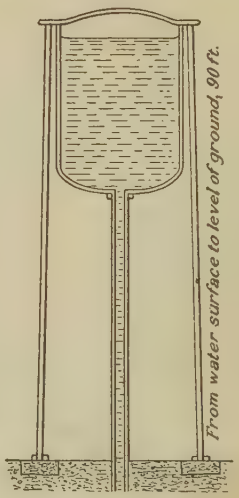


Fig. 33. — Standpipe.

the same depth with water. Compare the pressures in each case. How do you think the total force on the bottom in each case compares with the weight of the liquid?

7. How does your city get its water supply? Is the reservoir high enough to furnish sufficient pressure for fighting fires?

8. The pressure at the point of a phonograph needle may amount to several tons per sq. in. Explain how this is possible, since the reproducer weighs only a few ounces.

9. Why does a liquid exert pressure? Upon what factors does the intensity of liquid pressure depend? Of what factors is liquid pressure independent?

10. A dam is built across a river. Does the length of the river affect the total force of the water against the breast of the dam? Explain.

PROBLEMS

1. Find the pressure in pounds per sq. in. to which a diver is subjected if he descends to a depth of 200 ft. in sea-water, its density being 64 lb./cu. ft.

2. The surface of the water in a standpipe is 260 ft. above the level of a faucet. What pressure in lb. per sq. in. is exerted at the faucet?

3. What is the pressure in lb. per sq. in. when the water head is 500 ft.?

4. What water head is necessary to supply a pressure of 500 lb. per sq. in.?

5. Find the pressure in grams exerted by a column of mercury 76 cm. high. Density of mercury is 13.6 gm./c.c.

6. How high a column of water will be needed to exert the same pressure as the mercury column of Prob. 5? Express your answer in meters and also in feet.

7. The volcano Mauna Loa is 13,760 ft. high. Assuming that the crater is filled with molten rock having a density of 175 lb./cu. ft., calculate the pressure in lb. per sq. in. at the base. Can you see why the sides of volcanoes often split asunder?

8. A tank is 10 ft. square and 10 ft. deep. Find the total force on the bottom when it is filled with sea-water, density 64 lb./cu. ft. Calculate the total force on one side of the box.

9. A box 2 meters long, 160 cm. wide, and 800 mm. deep is filled with a liquid having a density of 1.4 gm./c.c. Calculate the total force on the bottom. On the longer sides. On the ends, or the shorter sides.

10. A tank 10 ft. deep is 10 ft. in diameter. It is full of gasoline, density 44 lb./cu. ft. Find the total force on the bottom and on the sides.

11. The breast of a dam is 20 ft. long; its vertical height is 30 ft. Find the total force against the dam when the water stands level with the top.

12. What force is required to hold a board tightly against a

hole 6 ft. long by 4 ft. wide in the side of a ship, if the average depth of the sea-water is 20 ft.?

13. Calculate the pressure exerted by sea-water at a depth of six miles.

14. The slanting bottom of a swimming pool is 100 ft. long and 30 ft. wide. The water is 4 ft. deep at one end and 8 ft. deep at the other end. Calculate the total force on the bottom, if the tank is full of sea-water. Calculate the total force on each end of the tank.

15. The walls of a vacuum bottle can withstand a pressure of 350 lb. per sq. in. To what depth in sea-water must this bottle be lowered in order to crush it?

16. A dam built across a stream is 400 ft. long and 40 ft. high. If the water stands level with the top of the dam, calculate the total force the dam must withstand.

B. PRESSURE APPLIED TO LIQUIDS

33. Introductory. The liquid pressure which we have been studying might be called *weight pressure* since it is due to the weight of the liquid itself. Solids also exert pressure on account of their weight, but not in a sidewise direction. If we put one end of a meter stick against the floor and push on the other end, it *transmits the pressure* to the floor in the direction in which the force acts. Since the stick is rigid, it transmits the pressure in *only one* direction. Suppose we put a stopper in one end of an iron pipe and completely fill the pipe with water. As a second stopper is pushed into the open end of the pipe, the first stopper is pushed out because the pressure is transmitted to it by the liquid in the pipe. Liquids are not easily compressed and readily transmit pressure. Now suppose we drill several small holes in the tube and repeat the experiment. As the second stopper is pushed into the pipe, the liquid squirts out through the holes, proving that pressure applied to a confined liquid is *transmitted in all directions.* This is what might be expected, if we pause to consider that the molecules of liquids move freely and slide over one another readily.

For the same reason we would expect gases to transmit applied pressure in all directions. When we inflate an automobile tire, pressure is applied at the valve stem to the air confined within the tire. Since all parts of the tire become equally hard, we may assume that this pressure is *transmitted equally in all directions.*

34. External Pressure Applied to Confined Liquids. A farm hand went to the well, filled a jug with water, inserted the stopper, and hit the stopper a sharp blow with the palm of his hand. The bottom fell out of the jug, much to his astonishment. Let us inquire what really happened. Fig. 34 represents the jug filled with water. As the stopper was driven into the jug by the force of the blow, *its pressure upon the confined liquid was transmitted equally in all directions.* For convenience, let us assume that the neck of the jug had an area of exactly 1 sq. in., and that 10 lb. of force were used in driving the stopper into the jug. That means that *every* square inch of the inside surface will be subjected to a pressure of 10 lb., *in addition to the weight pressure.* If the bottom of the jug had an area of 40 sq. in., then the total force acting upon it reaches the surprising total of 400 lb. The bottom of the jug was not strong enough to withstand so great a force.

FIG. 34. — Pascal's bottle.

35. Pascal's Law. Blaise Pascal, a French physicist, carried on a series of experiments in the study of the transmission of liquid pressure. By the use of "Pascal's vases" he had already shown that weight pressure of liquids is dependent upon the depth of the liquid, but independent of the shape of the container. He fitted pistons in the sides of a box filled with water. One piston had 100 times the cross-sectional area of the other. Pascal found that one man, pushing against the small piston, could equal the force of 100 men pushing against the large piston. (See Fig. 35.)

His own statement is as follows: "Hence it follows that a vessel full of water is a new principle in mechanics, and a new machine for multiplying forces to any degree we choose, since one man will by this means be able to move any given weight."

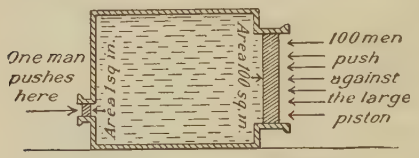


FIG. 35. — How man can multiply force.

The statement of this important principle of physics is known as PASCAL'S LAW. A brief statement follows: *Pressure applied anywhere to a body of confined or inclosed fluid is transmitted with undiminished force in every direction. This pressure acts at right angles to every portion of the surface of the container, with equal force upon equal areas.* Pascal's law applies to both liquids and gases.

36. Transmission of Liquid Pressure Used to Multiply Force. From Pascal's law, we are led to the following conclusion: If A of Fig. 36 has an area of 1 sq. in. and B an area of 100 sq. in., a weight of 1 lb. lying on the piston C will just balance a weight of 100 lb. on the piston D. A force *slightly* in excess of 1 lb. acting downward on the small piston will lift the weight of 100 lb. upon the large piston. From these observations, it is easy to see how it is possible to construct a mechanical device for multiplying force.

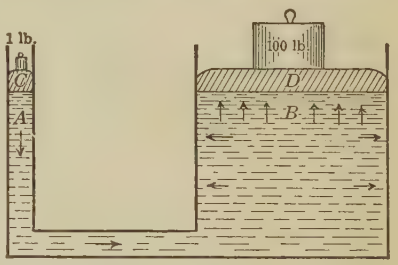


FIG. 36. — Pressure is transmitted equally in all directions.

The student, however, must never forget one very important fact. In the multiplication of force by any mechanical device, the distance and speed are correspondingly di-

minished. In other words, *what is gained in force is lost in distance and speed.* Suppose we force the piston C down 10 in.; just 10 cu. in. of water will be forced from A into B. The 10 cu. in. of water that are forced into the large cylinder will spread out over an area of 100 sq. in. Therefore it will raise its level and lift the large piston $\frac{10}{100}$, or 0.1 in. In the time required for C to move 10 in., D moves only 0.1 in., just 0.01 as far as C. The force of 1 lb. is multiplied 100 times by this device, but the object to be lifted on the large piston moves 0.01 as fast as the force applied to the small piston. In all mechanical devices, *the product of the acting force multiplied by the distance through which it moves equals the product of the resisting force multiplied by the distance through which it moves.* This is the general law of frictionless machines. Applied to this particular case, 1 lb. moving 10 in. is equivalent to 100 lb. moving 0.1 in.

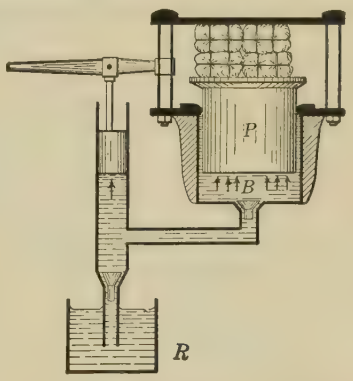


FIG. 37. — Diagram of hydraulic press.

37. The Hydraulic Press. The commercial hydraulic press is an application of Pascal's principle. By reference to Fig. 37, we may explain the operation of such a press. There are two cylinders, a small one and a large one. In each one there is a piston which fits so tightly that the liquid cannot be forced past it. A lever is attached to the small piston. As the small piston is pushed down, some of the oil or water from the small cylinder is forced over into the large cylinder B, and the piston P is lifted a trifle. As the lever is worked up and down, it continues to pump the liquid from the reservoir R, and force it into the cylinder

B. When the pressure is to be released, a valve not shown in the diagram is opened to let the liquid flow from *B* back into the reservoir.

The hydraulic press is used for baling cotton, paper, etc., squeezing the juice from apples and other fruits, expressing oil from seeds, punching holes in steel plates, embossing metals, and lifting enormous weights.

38. Mechanical Advantage. If we use a machine to multiply force, and find that an *acting* force of 1 lb. can counterbalance a *resisting* force of 5 lb., we say the *mechanical advantage* of the machine is 5. If the acting force is multiplied by 10 by the use of a machine, we say its mechanical advantage is 10. The mechanical advantage of a machine equals $\frac{\text{resistance}}{\text{effort}}$. Or, $M.\ A. = \frac{R}{E}$, in which R is the resistance and E the effort. The mechanical advantage may also be found by dividing the *distance the effort moves* by the *distance the resistance moves.*

If we neglect the effect of the lever, the *mechanical advantage* of the hydraulic press is equal to the area (A) of the large piston divided by the area (a) of the small piston. $M.\ A. = \frac{A}{a}$. If the diameters of the pistons are given, $M.\ A. = \frac{D^2}{d^2}$.

The student should recall that the areas of two circles are directly proportional to the squares of their diameters.

Hence, $E : R = a : A$

Or, $E : R = d^2 : D^2$, in which d and D represent the diameters of the pistons.

PROBLEM. A force of 500 lb. is applied to the small piston of a hydraulic press. Its diameter is 2 in. What resistance can be counterbalanced on the large piston, which is 40 in. in diameter?

Solution. The M. A. $= \frac{(40)^2}{(2)^2}$, or 400. If the machine multiplies

the effort by 400, then 500 lb. of effort can counterbalance 400 × 500 lb., or 200,000 lb. Or, we may use the formula, $E:R=d^2:D^2$. Whence 500: $x=(2)^2:(40)^2$. $x=200{,}000$ lb.

39. The Hydraulic Elevator. Two types of elevator are in common use. The *cable elevator* is lifted by means of a cable which passes over pulleys and is wound on a drum by means of an electric motor. The *hydraulic elevator* is an application of Pascal's law. The weight pressure of the water in the inlet pipe takes the place of the small piston. The large piston is a long shaft attached to the lower part of the cage itself.

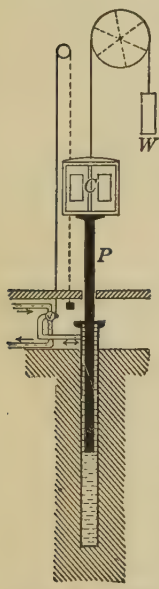


FIG. 38. — Hydraulic elevator.

As water from the city mains, or from a special reservoir, enters a cylindrical pit through the valve V, it exerts an upward pressure on the piston P, which is a strong shaft whose length equals the height of the building. (See Fig. 38.) Both the shaft P and the cage C are partially counterpoised by the weight W. The valve V is three-way. It may be opened to let the water flow from the reservoir into the pit. It may also be turned to let the water flow from the pit to the sewer, when the elevator descends. (See Fig. 39.)

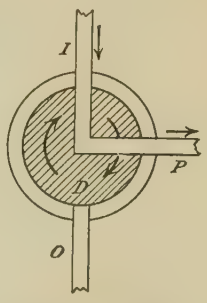


FIG. 39. — When disc turns through 90°, it connects P and O.

40. Other Applications of Pascal's Law. The *hydraulic jack* is used in lifting very heavy loads through short distances. Quite often Pascal's principle is used in the construction of *barbers'* and *dentists' chairs*. The manufacturers of *hydraulic brakes* claim that equalization of brake pressure is nearly perfect. The amount of pressure can be regulated

very easily, and it is also a simple matter to use the rear wheel brakes for the greater part of the braking force.

QUESTIONS

1. What are the advantages of the hydraulic elevator? What are its disadvantages?

2. Assuming that the story of the Dutch boy is true, how could he hold back the waters of the North Sea?

3. What would be the effect of applying the acting force to the large piston of a hydraulic press, and the resisting force to the small piston? (Use is made of such reversed application in launching airplanes from battleships.)

4. For sinking submarines during the war depth-bombs were used. They sank to a certain depth before exploding. How did liquid pressure aid in making them effective?

5. Is it possible to have a mechanical advantage of speed? Give a reason for your answer.

PROBLEMS

1. Water is supplied to a hydraulic elevator at a pressure of 80 lb. per sq. in. If the piston has a diameter of 10 in., what load can it lift?

FIG. 40. — Total force.

2. The small piston of a hydraulic press has an area of 1 sq. in. The area of the large piston is 200 sq. in. What is the mechanical advantage of the press? What force will be needed to balance a weight of 10 tons on the large piston?

3. The diameters of the pistons of a press are 1 in. and 8 in. respectively. What force must be applied to the small piston to lift a locomotive weighing 96 tons?

4. The two pistons of a press have areas of 1 sq. in. and 132 sq. in. respectively. If the large piston moves with a velocity of 0.5 ft. per sec., what velocity will be imparted to the small piston in ft. per sec.? In mi. per hr.?

5. By the use of a hydraulic press, 100 lb. must

lift 40,000 lb. If the diameter of the small piston is 1 in., calculate the diameter of the large piston.

6. The two pistons of a hydraulic press have diameters of 2 in. and 30 in. respectively. How heavy a load on the large piston can be lifted by a force of 400 lb. applied to the small piston?

7. The diameter of the piston of a hydraulic elevator is 8 in. If 400 lb. of the weight of the elevator are not counterpoised, at what pressure in lb. per sq. in. must the water be supplied to lift 10 people averaging 160 lb. each?

8. A cubical box is 20 cm. on a side. To the top a tube 1 sq. cm. in cross-sectional area and 180 cm. long is attached as shown in Fig. 40. Calculate the total force upon the bottom of the box, upon each side, and the upward force upon the top. Suppose we put a stopper in the tube and push down upon it with a force of 500 gm. Calculate the additional force on the bottom.

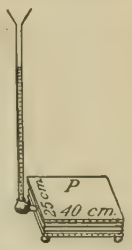


FIG. 41. — Hydrostatic bellows.

9. A man weighing 80 Kgm. stands upon the platform P of a hydrostatic bellows. (Fig. 41.) The platform is 25 cm. by 40 cm. He pours water into the tube. To what height above the platform must the water rise to balance the weight of the man?

C. ARCHIMEDES' PRINCIPLE

41. Buoyancy of Liquids. Pieces of cork and sticks of wood float on water. If the lungs are filled with air, the human body floats on water. Such facts furnish evidence that water exerts an upward pressure, or *buoyant force,* upon objects immersed in it. An object will float if the buoyant force of the water is greater than the weight of the object itself. (See Fig. 42.) Objects denser than water, even though they sink readily, appear to lose a part of their weight when submerged. For example, a man can lift a larger stone under water than he can possibly lift in air, because the buoyant force of the water lifts part of the weight. *The upward force any liquid exerts upon a body submerged in it is called its buoyancy.*

42. Measure of Buoyancy. Archimedes' Principle. Hiero, tyrant of Syracuse, ordered a crown made of pure gold. He handed the crown to Archimedes, asking him to determine whether any other metal had been used in its construction. Archimedes was puzzled to find a solution to this problem. While at his bath, he observed the buoyant effect of the water upon his body, and that the water rose in the tub as

FIG. 42. — The Naval hydroplane NC–4 was the first to cross the Atlantic Ocean. Her wing spread is 126 ft., and her extreme length 70 ft. The NC–4 was driven by four 400 H. P. Liberty motors. The carrying capacity is 14 tons. The flight of 4513 miles was made in 55 hr. and 33 min.

his body sank in the water. Then it occurred to him that he could use the buoyant effect of water upon the crown and upon pure gold to solve his problem. He is said to have rushed through the streets, shouting "Eureka, Eureka," meaning "I have found it" He had found the solution to his problem, for he reasoned that the buoyant force on his body must be equal to the weight of water displaced.

Let us perform a simple experiment and then see how the principle worked out by Archimedes helped him to solve Hiero's problem. The overflow can shown in Fig. 43 is filled with water up to the spout. A block heavier than water is weighed, first in air, and then in water. The differ-

Archimedes (B.C. 287–212) was born in Syracuse, Sicily. His works on arithmetic, plane and solid geometry, and mechanics are still extant. He applied mathematics to the theory of such simple machines as the lever, the pulley, and the screw. Archimedes is best known through the principle that bears his name. Aided by the mechanical devices of Archimedes, Syracuse withstood a long siege. When the city was finally captured, Archimedes was killed by a Roman soldier.

Blaise Pascal (1623–1662) was a famous French philosopher. Pascal was also a noted author. In mathematics he wrote a treatise on conic sections. The physics student remembers him best for his research on fluid pressure, as summarized by Pascal's law. He carried out further experiments to verify Torricelli's conclusions concerning air pressure.

ence between the two weights is the *loss of weight in water.* The block is then lowered into the overflow can. All the water which overflows, which just equals in volume the volume of the block, is caught and weighed. If the work was carefully done, we find as did Archimedes that the weight of the water displaced by the block exactly equals the loss of weight in water. This PRINCIPLE OF ARCHIMEDES may be stated as follows: *A body immersed in a fluid loses as much weight as the weight of the fluid it displaces.*

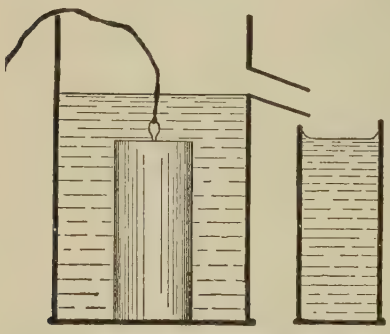


FIG. 43. — Overflow can with heavy object.

By applying this principle, Archimedes could compare the density of the crown with the density of a block known to be pure gold. Since gold is one of the densest of the metals, a piece of gold having a definite weight would have a smaller volume and would displace less water than a piece of silver of the same weight. For example, 1 lb. of gold displaces less water than 1 lb. of silver because its bulk is smaller. The relative volumes would be proportional to the losses of weight in water. Therefore, when Archimedes found that the crown lost more weight in water than the same weight of pure gold did, he knew that the crown was an alloy of some lighter metal.

43. Proof of Archimedes' Principle. Suppose we submerge in water a cubical block, 10 cm. on a side, to such a depth that its upper surface A is just 10 cm. below the surface of the water. (See Fig. 44.) The total *downward* force on the upper surface of the block equals 1000 gm. (Area = 100 sq. cm.; depth = 10 cm.; density = 1 gm./c.c.) The total *up-*

ward force on the surface B is 2000 gm. (Note that the surface B is 10 cm. deeper than A, or 20 cm.) The upward force at B exceeds the downward force at A by 1000 gm., and this block would lose 1000 gm., if weighed first in air and then in water.

The volume of a cubical block 10 cm. on a side is 1000 c.c. Since two things cannot occupy the same place at the same time, the block must displace 1000 c.c. of water. Since 1 c.c. of water weighs 1 gm., 1000 c.c. of water will weigh 1000 gm. Therefore, the block displaced 1000 gm. of water. But the buoyant force of the water on the block was also 1000 gm. Hence we may use the facts we learned concerning total force in liquids to prove that the *buoyant force which a liquid exerts upon a submerged body is equal to the weight of liquid the body displaces.*

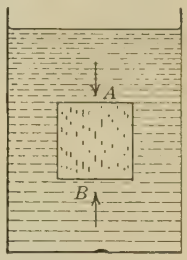


FIG. 44. — Buoyancy equals difference between upward and downward forces.

The student should compute the buoyancy when the *upper* surface of the block is submerged to a depth of 20 cm. below the surface of the water.

44. Principles of Flotation. From the preceding section, we find that the buoyant force upon a submerged body is exactly equal to the weight of the liquid displaced. If the weight of the body is more than the weight of the displaced liquid, it will sink. For example, suppose the block used in the preceding section weighs 1200 gm. The buoyant force of the water was only 1000 gm. Hence an additional upward force of 200 gm. would have to be used to keep the block from sinking. It loses 1000 gm. of its weight in water, but 200 gm. of its weight are unbalanced.

Suppose, however, that the block weighs in air only 800 gm. The buoyant force when the block is completely submerged is 1000 gm. Such a block, if pushed under water

and then released, would rise to the surface, because the upward force of the water is 1000 gm., and the downward force due to its weight is only 800 gm. To keep such a block submerged, an additional force of 200 gm. would have to be used. The block of Fig. 45 displaces its own weight of water before it is entirely submerged.

Let us use one more example. A person whose volume or bulk is just 2 cu. ft. weighs 130 lb. If he jumps into sea-water, the density of which is 64 lb./cu. ft., he will sink. The 2 cu. ft. of water displaced would buoy him up with a force of 128 lb., but his weight is 130 lb. It would take 2 lb. of force to keep him from sinking. Now suppose he uses just exactly 1 cu. ft. of cork as a life preserver. The cork weighs 15 lb. Now his total volume (body and cork) is 3 cu. ft., and the weight of water displaced would be 192 lb. His total weight (cork included) is 145 lb. Hence, it would need an additional force of 47 lb. to push him under water.

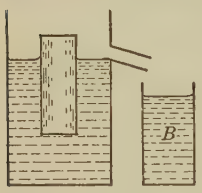


FIG. 45. — Overflow can and catch bucket.

We may summarize the LAWS OF FLOTATION as follows:
(1) *A body sinks in a fluid, if the weight of the fluid it displaces is less than the weight of the body.*

(2) *A submerged body remains in equilibrium, if the weight of the fluid it displaces exactly equals its own weight.*

(3) *If a body when submerged displaces a weight of fluid greater than its own weight, it will rise and float with a part of its volume above the surface.* Hence, a *floating* body displaces its *own* weight of liquid.

45. Floating Objects. If we place blocks of different kinds of light material on water, as shown in Fig. 46, we find that some sink deeper than others as they float. Suppose we select cubical blocks 10 cm. on a side. The volume in each case is 1000 c.c. Block *A* represents a piece of balsa wood. Block *B* represents a piece of cork, density 0.24 gm./c.c.

Its weight is 240 gm. Hence it must displace 240 gm., or 240 c.c., of water in order to float. When such a block is placed on the surface of the water, it will sink until 240 c.c. are submerged. This equals 0.24 of its volume, the same fraction as the density. Block *C* has a density of 0.75 gm./c.c. Since its weight is 750 gm., it will sink in water until 750 c.c. of its volume are submerged. The fractional part submerged is 0.75, the same fraction as the density. *D* represents a block of ice, having a density of 0.92 gm./c.c. Such a block weighs 920 gm., and it will sink until it displaces 920 c.c. of water. As ice floats in water, 0.92 of its volume is beneath the surface.

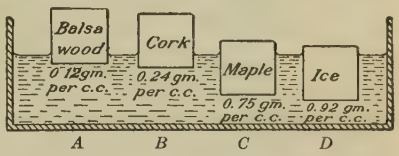


FIG. 46. — Some floating objects sink deeper than others.

If we lower block *B* into gasoline, which has a density of only 0.7 gm./c.c., it will sink deeper into the liquid before it displaces enough gasoline to equal its own weight; 240 gm. ÷ 0.7 gm./c.c. = 343 c.c., the volume of gasoline needed to weigh 240 gm. Hence 343/1000 of the volume, or approximately $\frac{1}{3}$, is submerged, when cork floats in gasoline.

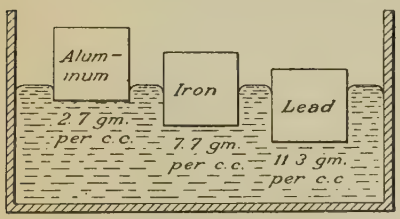


FIG. 47. — Some metals float on mercury.

Aluminum, iron, and even lead will float in a very dense liquid like mercury. The fractional part submerged is proportional to their relative densities. (See Fig. 47.)

46. Applications of Archimedes' Principle. The whole science of ship-building depends upon Archimedes' principle and the laws of flotation. A ship that weighs 4000 tons and carries a cargo of 8000 tons must be so proportioned as to length, breadth, and depth that it will displace 12,000

FIG. 48. — One of the U. S. battleships in Panama Canal. This battleship displaces 32,000 tons of water. Her armor plates are 14 in. thick, and the turret armor is 18 in. thick. The electrically driven engines develop over 30,000 horsepower, and drive the vessel 21 knots an hour. This battleship carries eight 14-inch guns of 50 caliber (almost 60 ft. long). Such guns fire a projectile weighing 1400 lb. and have an effective range of more than 12 miles. The full complement of officers and men numbers more than 1500. (*U. S. Official.*)

tons of water. Some of our largest battleships displace 32,000 tons of water. (See Fig. 48.) For every 64 lb. of weight an ocean vessel carries, one cu. ft. of sea-water must be displaced. The pontoon bridge, the floating dry-dock, and the submarine are all applications of these principles.

A person can float in salt water more easily than in fresh water, because the density of the salt water is slightly greater. The use of the ordinary life-preserver is an application of the third law of flotation. It adds but little to the weight of the wearer, but it increases his volume very greatly; hence the combination displaces more water. The various methods of finding the density of solids and liquids depend upon Archimedes' principle. The various types of buoys are all applications of the principle of flotation. The supply of gas by means of the carburetor is controlled by a floating device, and a floating ball closes the valve which shuts off the water supply in the tank of the lavatory.

QUESTIONS

1. Do you think you could float in a tank of gasoline? Give a reason for your answer?

2. Explain how a battleship, which is covered with steel plates from 10 to 18 in. thick, can float on water.

3. Given a flat-boat. Explain how you could use this boat to find the weight of a locomotive.

4. Does a boat rise or sink deeper as it goes from fresh water into salt water? Explain.

5. In general, what fractional part of a floating body is submerged as it floats in water?

6. Would a solid iron ship float in mercury?

7. How do boat-builders utilize Archimedes' principle and the laws of flotation?

8. What principle is involved in the use of the floating buoy?

9. What do we mean when we say that the displacement of a vessel is 30,000 tons?

10. By deep breathing an adult can inhale about a gallon of air. Explain how this fact affects his ability to float in water.

11. When eggs begin to decompose gases accumulate within the shell. How could you use a salt water solution to test the freshness of eggs?

12. In pulling up an anchor, why does it seem so much heavier just as it is lifted above the surface of the water?

PROBLEMS

1. A cubical block of wood 10 cm. on a side floats in water. Its density is 0.7 gm./c.c. Find, (a) the volume of the block; (b) its weight; (c) what fractional part of the block is above the surface of the water; (d) what force is required to sink the block.

2. A weighted stick 12 in. long sinks to a depth of 8 in. in water. Find the density of the stick.

3. How deep will the stick of Prob. 2 sink in alcohol having a density of 0.8 gm./c.c.?

4. A canoe weighs 80 lb. How many cu. ft. of water must it displace to carry 3 persons who weigh 150 lb. each?

5. A person displaces 2.5 cu. ft. of sea-water as he floats. What is his volume? What is his weight in air? His apparent weight in water?

6. A flatboat is 40 ft. long and 20 ft. wide. It sinks in sea-water to a depth of 2 ft. when a load is taken aboard. How heavy is the load?

7. A cube of iron 10 cm. on a side weighs 7600 gm. in air. What will it weigh in water? What will it weigh in a liquid that weighs 0.8 gm./c.c.? What will it weigh in mercury, density 13.6 gm. per c.c.?

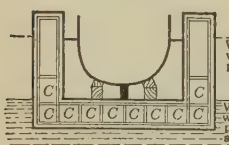


Fig. 49. — Floating dry-dock.

8. A block of wood is 4 ft. long, 2 ft. wide and 1 ft. thick. If it weighs 350 lb., what force is needed to push it under water?

9. A block of ice 10 ft. long, 8 ft. wide, and 2 ft. thick floats with 0.9 of its volume submerged in sea-water. Calculate the weight of the ice, and the force needed to submerge it.

10. The head of a hammer weighs 1520 gm.; its density is 7.6

gm./c.c. The handle has a volume of 2000 c.c., and a density of 0.7 gm./c.c. If the combination is thrown into a vessel of water, what force is needed to keep it from sinking?

11. If the hammer described in Prob. 10 is thrown into a liquid having a density of 1.4 gm./c.c., will it sink or float? What force is needed to keep it from sinking or floating?

12. A floating dry-dock has 10 compartments. (See Fig. 49.) Each compartment is 15 ft. wide by 15 ft. high by 1000 ft. long. How heavy a vessel can this dry-dock float?

D. DENSITY AND SPECIFIC WEIGHT

47. Density and Specific Weight. In several problems we have made use of the density of various substances. Quite frequently it is desirable to know how many times as dense one substance is as another. It is still more simple to choose a standard and compare the densities of all other substances with that standard. Water is the standard used for *specific* weights of solids and liquids. For gases, the standard used is either air or hydrogen. In physics the word *specific* implies a ratio, or a comparison with some standard. *Specific weight, or specific density, may be defined as the ratio of the weight of a substance to the weight of an equal volume of some standard substance.* Specific weight is commonly called *specific gravity.*

Specific weight is an *abstract* number telling "how many times as heavy" a substance is as an equal volume of water. For example, 1 c.c. of copper weighs 8.8 gm.; the *concrete* number, 8.8 gm./c.c., expresses the density of copper in the Metric system. Since 1 c.c. of water weighs only 1 gm., then copper is 8.8 times as dense as water. The quotient (8.8 gm. $\div$ 1 gm.) is an *abstract* number, the same numerically as the density.

In the English system the density of copper is 549.12 lb./cu. ft., and the density of water is 62.4 lb./cu. ft. By dividing, we find that the copper is 8.8 times as dense as the water. If both had been weighed in ounces or in tons,

the ratios of their densities would have been the same. The copper has a specific weight of 8.8, quite a different number from its density. In the English system, *density is 62.4 times the specific weight*, because 1 cu. ft. of water weighs 62.4 lb. In the Metric system, *density is 1 times the specific weight*, because 1 c.c. of water weighs 1 gm.

48. Methods of Finding Specific Weight. Since specific weight equals $\frac{\text{density of } x \text{ substance}}{\text{density of water}}$ we could find the specific weight of a substance by finding its density and comparing its density with that of water. But the following is also true:

$$\text{Specific weight} = \frac{\text{weight of } x \text{ substance}}{\text{weight of same volume of water}}.$$

By the use of Archimedes' principle we can easily find the weight of the same volume of water, since a body submerged in water loses as much weight as the weight of the water displaced. In general, finding the specific weight of a substance requires three steps: (1) finding its weight; (2) finding its loss of weight in water (weight of same volume of water); (3) dividing its weight by the weight of the same volume of water.

(*a*) *Specific weight of a solid heavier than water.* To find the specific weight of a heavy solid, insoluble in water, we first weigh the solid in air, and then in water. The *difference* between the two weights equals the weight of the same volume of water. Therefore:

$$\text{Specific weight} = \frac{\text{weight in air}}{\text{loss of weight in water}}.$$

Problem. A stone weighs 30 gm. in air and 20 gm. in water. Find its specific weight.

Solution. Loss of weight in water is 10 gm. Then, 30 gm. $\div$ 10 gm. = 3, the sp. wt. The volume of the stone must have been 10 c.c., since 1 c.c. of water weighs 1 gm.

(*b*) *Specific weight of a solid lighter than water.* Since a floating object loses all of its weight in water, it is more difficult than with heavy solids to find its volume, or "the weight of the same volume of water." This can be done by the use of a sinker. We find the buoyant effect on the sinker alone, and then the buoyant effect upon the light solid with sinker attached. The difference is the buoyant effect upon the light solid. We proceed as follows: (1). We weigh the solid in air, and call its weight w. (2). We find the combined weight, solid in air and sinker in water, calling this weight w'. (See Fig. 50). (3). Then we find the combined weight when both are submerged, calling this weight w''. The difference between w' and w'' equals the buoyant force of the water on the solid alone, or it is the weight of a volume of water equal to the volume of the solid. Hence,

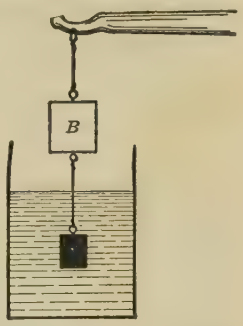


FIG. 50. — Specific weight of bodies lighter than water.

$$\text{Sp. wt.} = \frac{w}{w' - w''}$$

PROBLEM. A piece of cork weighs 50 gm. A sinker immersed in water weighs 210 gm. The combined weight of the cork and sinker when submerged is 10 gm. Find the sp. wt. of the cork.

Solution. Sp. wt. $= \frac{w}{w' - w''}$. The weight of an equal volume of water is found by subtracting 10, the weight of both when submerged, from 260, the combined weight of cork in air and sinker in water. Then $50 \div 250 = 0.2$, sp. wt. of cork.

(*c*) *Specific weight of liquids.* (*Bottle method.*) A small flask or bottle like that shown in Fig. 51 may be used to find the specific weight of liquids. We first find the weight of the empty bottle, and then find the weight when the bottle is filled with water. The difference equals the weight of

water the bottle can hold. Next the bottle is filled with the liquid of unknown specific weight and again weighed. Subtracting the weight of the empty bottle, we find what weight of x liquid the bottle can hold. Then,

$$\text{Sp. wt.} = \frac{\text{weight of } x \text{ liquid}}{\text{weight of same volume of water}}.$$

FIG. 51. — Pycnometer.

EXAMPLE. A small bottle weighs 22 gm.; filled with water it weighs 72 gm.; filled with alcohol it weighs 62 gm. Find the specific weight of the alcohol.

Solution. The bottle holds 50 gm. of water. It holds 40 gm. of alcohol. The specific weight of alcohol equals $\frac{40}{50}$, or 0.8.

(*d*) *Specific weight of liquids.* (*Loss of weight method.*) The denser a liquid, the greater its buoyancy. Hence we can find the relative weights of two liquids by comparing their buoyant effects upon some solid. A bulb, usually of glass or platinum, is weighed in air, then in water, and finally in the liquid whose specific weight is to be determined. The bulb will displace the same volume of each liquid. If it loses twice as much weight in one liquid as in water, that liquid must be twice as dense as water.

$$\text{Therefore: Specific weight} = \frac{\text{loss of weight in } x \text{ liquid}}{\text{loss of weight in water}}.$$

EXAMPLE. A ball weighs 40 gm. in air, 32 gm. in water, and 28 gm. in a liquid of unknown density. Find the specific weight of the liquid.

Solution. Loss of weight in x liquid is 12 gm.; the loss of weight in water is 8 gm. The buoyancy of the x liquid compared with the buoyancy of water is $\frac{12}{8}$ or 1.5. Therefore the specific weight of the liquid is 1.5.

(*e*) *Specific weight of liquids.* (*Hydrometer method.*) A wooden rod, loaded at one end so it will float vertically,

sinks in water until the weight of the water it displaces exactly equals its own weight. Placed in a liquid of unknown specific weight it sinks until the weight of x liquid displaced equals its own weight. If the rod is uniform, the relative volumes of liquids displaced will be proportional to the depths to which the rod sinks. For example, if the rod sinks 10 cm. in water, and to a depth of 8 cm. in x liquid, then x liquid is $\frac{10}{8}$, or 1.25 times as heavy as water.

$$\text{Sp. wt.} = \frac{\text{depth rod sinks in water}}{\text{depth rod sinks in } x \text{ liquid}}.$$

The *commercial hydrometer*, Fig. 52, has a scale so graduated that the specific weight of the liquid in which it floats may be read directly. The upper bulb is designed to increase the volume of the hydrometer, while the lower bulb is filled with shot or mercury so the vertical position of the hydrometer will be maintained as it floats.

Fig. 52. — Hydrometer.

The hydrometer finds many uses. As the storage battery in our radio set or our automobile loses its charge, the specific weight of the liquid becomes less. The hydrometer is a very convenient instrument for telling whether the battery needs recharging. Milk is slightly denser than water. A special hydrometer called a *lactometer* may be used to determine whether water has been added to milk. (See Fig. 53.) The common acids are denser than water. The ordinary hydrometer, or a special hydrometer called an *acidimeter*, is used to test the concentration of acids. Alcohol is much lighter than water. The *alcoholometer* is a hydrometer used to determine the per cent of alcohol in a mixture of alcohol and water. The concentration of a solution, or the purity of a liquid, may be determined by testing its specific weight.

SUMMARY

Liquids have weight; therefore they exert pressure on the bottom and sides of the containing vessel. Liquid pressure is directly proportional to the depth and density of the liquid; it is independent of direction.

Fig. 53. — Lactometer.

The total force exerted upon any surface by a liquid equals the product of the area times the average depth times the density.

Pressure applied to any part of a confined fluid is transmitted so as to act with undiminished force in every direction. Such pressure acts with equal force upon equal areas. This principle is known as Pascal's law.

Pascal's law finds application in the hydraulic press and the hydraulic elevator. By sacrificing speed, a small force may be used to overcome a very great resistance. In all frictionless machines, acting force times the distance the acting force moves equals resisting force times the distance the resisting force moves.

The upward force a fluid exerts on a submerged body is called its buoyancy. Archimedes found that the magnitude of this buoyant force just equals the weight of the fluid displaced.

The buoyant force on a solid immersed in water must be *greater than* its weight, exactly *equal to* its weight, or *less than* its weight. In the first case the solid will rise to the surface and float with a part of its volume submerged. In the second case, it remains in equilibrium in the liquid; and in the third case, it sinks.

Density is the weight per unit volume. Specific weight is the weight of a certain volume of substance divided by the weight of the same volume of water.

QUESTIONS

1. Some hydrometers are made for use with liquids denser than water. Others are made to be used for light liquids. How do you think they would differ in construction?

2. Denatured alcohol is mixed with water for use in automobile radiators in winter. The larger the per cent of alcohol, the lower the freezing point of the mixture. How can the hydrometer be used to test the freezing point of the mixture?

3. Some radio batteries have colored balls floating in the acid solution. What principle is involved in their use?

4. Suppose you were handed a crown and asked to find out whether it was made of pure gold. Without destroying the crown, how would you proceed?

5. A cube of iron loses 100 gm. when submerged to a depth of 1 m. How much will it lose when submerged to a depth of 10 m.?

6. Which do you think has the higher specific weight, whole milk or skim milk? Give a reason for your answer.

7. Name as many uses as you can for the hydrometer.

8. Why are density and specific weight the same numerically in the Metric system? Why are they different in the English system?

PROBLEMS

(See table of specific weight in appendix.)

1. A block of iron weighs 40 gm. in air and 34.8 gm. in water. Find the sp. wt. of the iron. Find the weight of 1 cu. ft. of iron.

2. A block of aluminum weighs 40 gm. in air and 25.2 gm. in water. Find the sp. wt. of aluminum. Explain why 40 gm. of aluminum lose so much more weight in water than 40 gm. of iron.

3. What is the meaning of the expression, "The sp. wt. of lead is 11.3."? What will 10 c.c. of lead weigh in air? In water? In alcohol, whose sp. wt. equals 0.8?

4. How much weight will 20 c.c. of gold lose in water? 20 c.c. of silver?

5. How much weight will 20 gm. of gold lose in water? 20 gm. of silver?

6. A body weighs 400 lb. in air and 300 lb. in water. Find its sp. wt. Calculate its volume. Find its density.

7. A block of wood weighs 50 gm. in air; a sinker weighs 140 gm. in water; the combined weight of the wood and sinker in water is 120 gm. Find the sp. wt. of the wood.

8. A block of paraffin weighs 40 gm. in air. A sinker weighs 215 gm. in water. Both paraffin and sinker weigh 211 gm. in water. Find the sp. wt. of the paraffin.

9. A piece of cork weighs 30 gm. in air. A sinker weighs 170 gm. in water. Both cork and sinker weigh 50 gm. in water. Find the sp. wt. of the cork.

10. A block of wood weighs 80 gm. in air. When attached to a sinker, which weighs 30 gm. in water, the combination weighs zero in water. Calculate the sp. wt. of the wood.

11. A flask weighs 30 gm. Filled with water, it weighs 80 gm.; filled with salt water, it weighs 86.5 gm.; filled with gasoline, it weighs 65 gm. Find (a) sp. wt. of salt water; (b) sp. wt. of gasoline.

12. A flask weighs 30 gm. Filled with water, it weighs 55 gm.; filled with chloroform, it weighs 67.5 gm.; and filled with turpentine, it weighs 52 gm. Find (a) the volume of the flask; (b) the sp. wt. of the chloroform; (c) the sp. wt. of the turpentine.

13. A glass bulb weighs 60 gm. in air, 30 gm. in water, and 6 gm. in sulphuric acid. Find (a) the volume of the bulb; (b) the sp. wt. of the bulb; (c) the sp. wt. of the acid.

14. A body weighs 40 gm. in air; its apparent weight when submerged in water is zero. Find its sp. wt.

15. What is the specific weight of a substance that loses half its weight in water? What is the sp. wt. of a substance that floats with just half its volume submerged?

16. A glass stopper weighs 80 gm. in air and 40 gm. in water; in a liquid of unknown sp. wt., it weighs 50 gm. Find the sp. wt. of the liquid.

17. A wooden rod 12 in. long sinks in water to a depth of 9 in. Find its sp. wt. If it sinks in oil to a depth of 10.5 in., find the sp. wt. of the oil.

18. Mercury has a sp. wt. of 13.6, and lead a sp. wt. of 11.3.

What fractional part of a block of lead is submerged as it floats in mercury?

19. What fractional part of an iceberg, sp. wt. 0.92, is submerged as it floats in sea-water, sp. wt. 1.026?

20. A boy can lift 150 lb. If a stone has a sp. wt. of 3, how many cu. ft. of stone can he lift? How many cu. ft. of stone can he lift to the surface of a pond?

CHAPTER 3

MECHANICS OF GASES

A. THE ATMOSPHERE

Vocabulary

Caisson, a water-tight chamber used for construction work under water.

Dehydrate, to remove water from a food or other substance.

Pneumatics, that branch of physics that deals with the mechanical properties of gases.

Unbalanced, applied to a greater force on one side of an object than exists on the opposite side.

49. Air Has Weight. The expression "light as air" is used so frequently that one is apt to get the idea that air has no weight, or that its weight is negligible. We speak of an empty bottle, when we refer to a bottle that is full of air. The following simple experiment shows that the weight of air is appreciable.

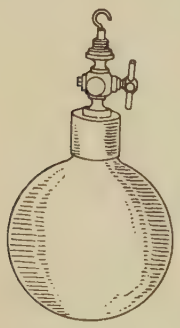


Fig. 54. — Baroscope globe.

Find the weight of a glass bulb fitted with a stop cock. (See Fig. 54.) Pump the air out of the bulb, close the stopcock, and weigh it again. Its weight will be less than before. Or we may weigh an electric light bulb, which is practically a vacuum. The gas-filled bulbs cannot be used. When a hole has been made in the bulb by directing the tip of a blowpipe flame against one side, the air rushes in, and the bulb shows an increase in weight. Thus we see that air has weight and that it takes up space. It can be pumped into pneumatic tires or pumped out of

vessels with a vacuum pump. Careful experiments show that *one liter of air at a temperature of 0° C. and under a pressure of one atmosphere, or 76 cm. of mercury, weighs 1.293 gm.* (See § 62.) It is about $\frac{1}{773}$ as heavy as an equal volume of water.

Although air is light when compared to water, yet in any considerable quantity the weight of air becomes an important factor. At sea level 1 cubic foot of air weighs a trifle more than $1\frac{1}{4}$ oz., and 1 cu. yd. a little more than 2 lb. The air in a room 18 by 18 by 12 ft. weighs a little more than 300 lb.

Air is the *popular* standard for determining the specific weight of gases, although hydrogen is a more scientific standard. Hydrogen is the lightest gas known, and when it is taken as unity no gas can have a specific weight less than one. Some gases are several times as heavy as air, while several of them are slightly lighter.

50. Air Exerts Pressure. We move about in the air so easily that we are unconscious of its pressure. But if we go down into a deep mine or up in an elevator, our ear-drums are sensitive to the change in air pressure. If we tie a thin rubber membrane over a bladder glass, as in Fig. 55, and then exhaust the air by means of an air pump, the rubber is forced down into the glass until it will probably burst. Exhausting the air removes the *upward* air pressure, leaving an unbalanced *downward* pressure.

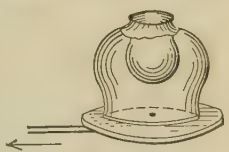


FIG. 55. — Air exerts pressure.

We may also use an empty varnish can to show air pressure. Let us take a can of one-half gallon capacity, put into it a little water, and then heat the water to boiling. The steam that forms drives all the air out of the can. Next let us stopper the can tightly and cool it by holding it under running water. As the steam condenses and produces a

vacuum inside, the unbalanced outside pressure crushes the can. Common sense tells us that if air has weight, it must exert pressure.

Like liquids, gases are fluid, although they are more mobile; their elasticity is almost perfect. Therefore, the facts we have already learned concerning liquid pressure and the principle of Archimedes apply to gases as well as to liquids.

Although we really live at the bottom of an "ocean of air," we do not feel the pressure which the atmosphere exerts, because the pressure is nearly equal in all directions. When we see the wind breaking the limbs of trees, uprooting trees bodily, or toppling over buildings, then we begin to realize the enormous pressure which the air can exert.

51. Liquids Rise in Exhausted Tubes. Every time we suck soda water through a straw we demonstrate the fact that liquids rise in exhausted tubes. The Greeks and Romans explained this phenomenon by saying that "Nature abhors a vacuum,"—the liquid rising to take the place of the air which is removed by suction. Just how absurd this idea is may be pictured if we try to imagine nothing (a vacuum) pulling something up the tube.

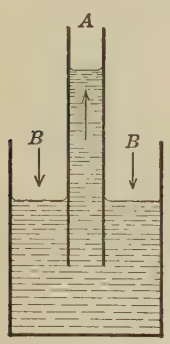


FIG. 56. — Liquids rise in exhausted tubes.

About the middle of the 17th century the Duke of Tuscany had a well dug, but he found that the water would not rise more than 32 ft. in the tube of the pump he was using. Then he went to Galileo for an explanation. The aged philosopher answered, "Evidently nature's horror of a vacuum does not extend beyond 32 feet."

Whether Galileo knew the correct reason is uncertain. He did know that air has weight and probably suspected that it was the pressure of the atmosphere that pushed liquids up exhausted tubes. (See Fig. 56.) He devised an experiment

to explain this phenomenon, but his death in 1642 occurred before he had time to complete it. Torricelli, his pupil, continued the experiment that explains conclusively why liquids rise in exhausted tubes.

52. Torricelli's Experiment. Torricelli reasoned that if water would rise 32 ft. in an exhausted tube, and no more, mercury, which is 13.6 times as dense as water, would rise only $\frac{1}{13.6}$ as high. He took a glass tube about three feet long, closed at one end, and filled it with mercury. Placing his finger over the open end of the tube, he then inverted it in a bowl of mercury. (See Fig. 57.) When he removed his finger, only a little mercury flowed out of the tube. The mercury column, AB, stood about 30 in. above the level of the mercury in the bowl. This is what he had expected, since 32 ft. $\div$ 13.6 gives about 2.5 ft., or 30 in. Therefore he proved that a column of mercury 30 in. long is just counterbalanced by the pressure which the atmosphere exerts at sea level. So you can see why it is not strictly correct to say that liquids "rise" in exhausted tubes; they are pushed up the tube by the pressure of the atmosphere on the surface of the liquid outside the tube.

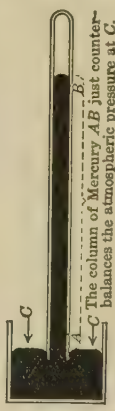


FIG. 57. — Torricelli's apparatus.

53. Pascal's Experiment. When Pascal learned of Torricelli's experiment, he was not entirely convinced that his explanation was correct. He reasoned that if the mercury column in a Torricellian tube was actually sustained by the pressure of the atmosphere, the height at which such a column stands would be less at higher altitudes than at sea level. He carried a Torricellian apparatus to the top of a tower in Paris and found a slight decrease in the height of the mercury column. Then he wrote to his brother-in-law, requesting him to repeat the experiment by carrying a

Torricellian apparatus to the top of Puy-de-Dôme, a mountain about 1000 meters high. The mercury fell about 8 cm. in the tube as he made the ascent, and he wrote to Pascal that he was "ravished with admiration and astonishment." We know that water pressure increases with the depth. Since the atmosphere is an "ocean of air," we are not surprised that the pressure in the valleys is greater than it is on the mountain tops. There is this difference, however: air is so compressible that its density varies with the altitude, while the density of water is not much affected by the depth.

54. Magnitude of the Atmospheric Pressure. The experiments begun by Torricelli and elaborated by Pascal prove conclusively that the height to which a liquid will rise in an exhausted tube depends upon the pressure of the air on the surface of the liquid outside the tube. The average of a large number of experiments shows that the air at sea level exerts sufficient pressure to counterbalance a mercury column 76 cm. high (about 30 in.). Since we know how to calculate fluid pressures, we can find the magnitude of the pressure which the air exerts. Since pressure equals depth times density, we multiply 76 cm. by 13.6 gm./c.c. Thus we find that the air pressure is 1033.6 gm. on every square centimeter of surface at sea level.

In the English system, 30 in. = 2.5 ft., the depth. The density of mercury = 62.4×13.6 (its sp. wt.), or 848.6 lb./cu. ft. Then the pressure in lb. per sq. in. = $\frac{2.5 \text{ ft.} \times 848.6 \text{ lb./cu. ft}}{144}$. The pressure is 14.7 lb. per sq. in., which is known as the "pressure of one atmosphere." "Two atmospheres pressure" would equal 29.4 lb. per sq. in.

If we made a Torricellian tube to be filled with water, it would need to be 13.6×30 in., or 34 ft. long. If the atmosphere exerts only enough pressure at sea level to raise a column of water 34 ft., we can readily understand why the Duke of Tuscany's pump would not lift water more than

32 ft., since no pump can produce a perfect vacuum. Fig. 58 shows three fluids that exert equal pressures.

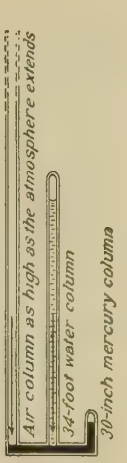


FIG. 58. — All have the same pressure.

55. The Magdeburg Hemispheres. In 1650 Otto von Guericke, Mayor of Magdeburg, conceived the idea that air, which he believed to be a substance, could be pumped out of a container. In that year he invented the *air pump*, or *vacuum pump*, probably being at the time entirely ignorant of the work of Torricelli and Pascal. He was anxious to learn whether any peculiar effects could be observed in the space, or vacuum, from which the air had been exhausted.

Incidentally he devised a striking experiment which helps to give us an idea of the enormous pressure of the outside air upon a vessel from which the air has been pumped. He made two hollow hemispheres, about 22 in. in diameter. The edges were

FIG. 59. — Otto von Guericke's experiment as performed at Magdeburg.

ground so smooth that when covered with a heavy grease and placed together they fitted air-tight. He then pumped the air out of the hemispheres and closed the stopcock. In a demonstration held in the presence of the Emperor and the Reichstag, it is said to have required 16 horses, 4 teams on each side, to pull the hemispheres apart. (See Fig. 59.) Small hemispheres of this type are found in every physics laboratory. Although they are usually only 3 or 4 in. in diameter, two strong boys cannot pull them apart when they are fitted air-tight and evacuated. (See Fig. 60.)

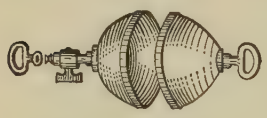


Fig. 60. — Magdeburg hemispheres.

56. The Mercurial Barometer. A barometer is used to *measure* the pressure of the air at any given place or time. If we have a Torricellian tube and bowl, it is a simple matter to make a barometer. We need a support for the tube and a measuring stick to find the height of the mercury column. Sometimes the tube is attached to a board upon which a scale is marked; in other cases a measuring stick is fastened to the board alongside the tube. Quite often a metal tube is used as a frame to support the tube and bowl, and to protect them against breakage. (See Fig. 61.) The scale in inches or centimeters is etched on the metal tube. Such a tube is cut away near the top so the level of the mercury in the Torricellian tube can be seen and measured.

If the air pressure grows less, some of the mercury will flow out of the tube into the bowl, and conversely. This changes the level. In order to have a fixed point from which to measure the

Fig. 61. — Mercurial barometer.

height of the column, a small pointed ivory peg is mounted on the frame just inside the bowl. The point of the peg is used as the zero mark of the scale. By means of a flexible membrane and a thumb-screw, as shown in Fig. 62, the surface of the mercury in the bowl can always be raised or lowered to coincide with the tip of the ivory peg, and this should always be done before any readings are taken.

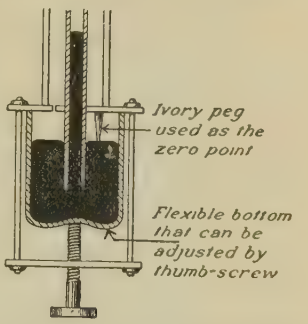


FIG. 62. — Bowl of barometer.

Mercury is suitable for use in these cistern barometers, as they are sometimes called, because it has a high specific weight, and it does not freeze readily. It does expand, however, with an increase in temperature. Hence readings taken with a mercurial barometer must be corrected for temperature changes.

57. The Aneroid Barometer. Since the mercurial barometer described in the preceding section must be at least 3 ft. in length, it is awkward to handle. It is not easily portable, and it must hang in a vertical position. Hence such a barometer would not be satisfactory on a rolling ocean vessel, or on an airplane, especially one in which the aviator wished to loop-the-loop.

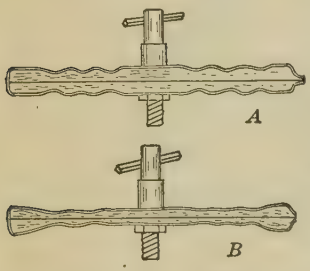


FIG. 63. — *A*. Corrugated box for aneroid barometer, partially exhausted. *B*. Corrugated box flattened by air pressure.

The *aneroid* (without liquid) barometer is convenient, and it is not affected by a change in position. It consists essentially of a shallow box, having a thin, corrugated metal cover. (See Fig. 63.) Since this box is a partial vacuum,

the *elastic* cover is very sensitive to changes in atmospheric pressure. The base of the metal box is fastened to the base of the instrument. As the top moves up or down in response to pressure changes, its motion is communicated to a system of levers. A slight motion of the elastic cover applied to the short end of a lever is multiplied at the long end of the lever. By such multiplying devices, it becomes easy to perceive the slightest change in the diaphragm, or metal cover. The lever motion is communicated by a chain or cord to a pointer that moves over a graduated scale. (See Fig. 64.)

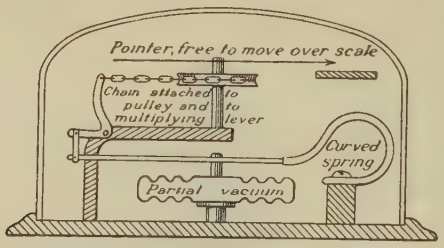


FIG. 64. — Diagram to show operation of aneroid barometer.

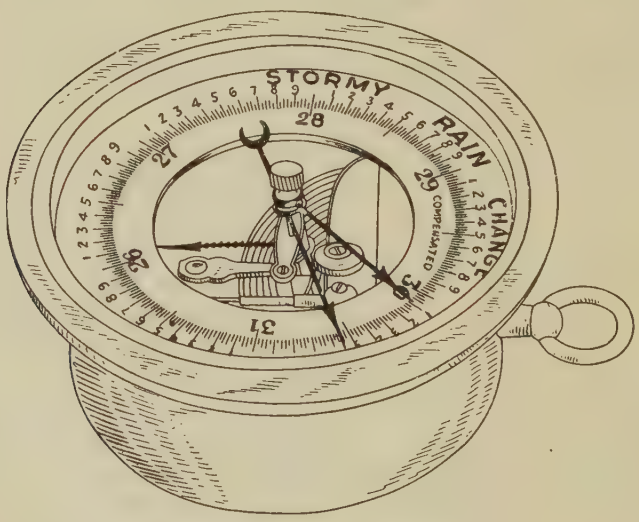


FIG. 65. — Aneroid barometer.

Of course this scale must be graduated or calibrated by comparison with a standard mercurial barometer.

The aneroid barometer may be made of practically any size. Some are small enough to be carried in the pocket

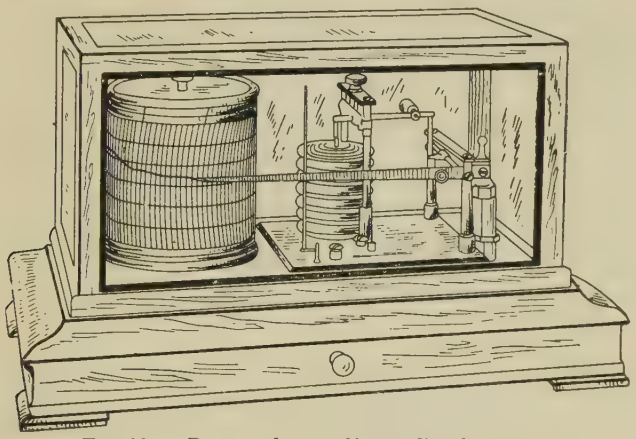


Fig. 66. — Barograph, or self-recording barometer.

like a watch. Many of them are about the same size as an ordinary alarm clock. A good aneroid barometer is so sensitive that it shows a change of pressure when lowered from a table to the floor. (See Fig. 65.)

The self-recording aneroid barometer, or *barograph*, carries a long pointer which traces in ink a continuous record of the atmospheric pressure. (See Fig. 66.) Sheets of paper are marked with horizontal lines to indicate pressures, and vertical lines to show the days and hours of the week. These sheets are fastened to a cylinder which is turned by clock-work through one complete revolution in one week. As the paper turns on the cylinder, the pointer traces a continuous line that shows the pressure for any time during the week. Sheets of this kind may be filed as a permanent record of the atmospheric pressure. Fig. 67 shows such a

record made at Newark, N. J., for the week beginning March 21, 1927.

58. Uses of the Barometer. (*a*) *To measure altitudes.* For many years the barometer has been used to measure alti-

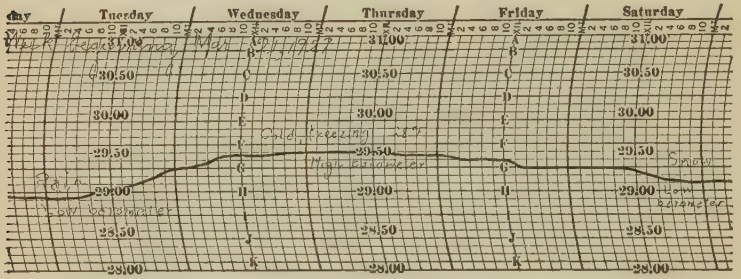


FIG. 67. — Note that high barometer is associated with low temperatures and vice versa.

tudes. At the present time it is used more extensively than before, since the determination of altitudes is of so much importance to aviators and balloonists. Aneroid barometers for use on airplanes are graduated to read altitudes directly. They are called *altimeters.*

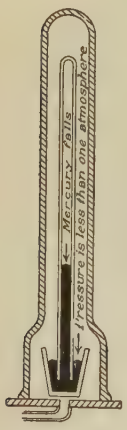


FIG. 68. — Mercury falls as pressure is reduced.

For comparatively small elevations, the barometer falls 0.1 in. for every 90 ft. of ascent. The fall is not so regular above a few hundred feet. At the top of Mt. Blanc (15,880 ft.) the barometer reading is approximately half what it is at sea level, while at the top of Mt. Everest (29,002 ft.) the barometer reading is less than 10 in.

By putting a Torricellian apparatus in a bell glass so that the air pressure may be reduced by means of a vacuum pump, as shown in Fig. 68, we can very easily see what happens to the mercury column as we pump out the air

from the bell glass. Without climbing a mountain, we observe exactly what happens as the air pressure is lowered.

(*b*) *To forecast weather.* The beginner in physics is generally astonished to learn that *dry* air is heavier than *moist* air. But water vapor is only about 0.6 as heavy as air. Hence the more moisture the air contains the less pressure it exerts. For that reason the barometer falls in moist weather. This fact is just contrary to the popular belief that moist air is *heavy.* It is *oppressive,* but really less dense than dry air. Such errors often occur through our misuse of the English language. We speak of a "heavy" cream, when we mean a "thick" cream. Cream is light enough to float on milk, and "extra heavy cream" is actually lighter than "heavy cream."

A rising barometer shows that the density of the air is increasing. Hence,

A rising barometer indicates fair or clearing weather.

A rapidly falling barometer indicates an approaching storm.

Continued high barometer indicates steady, fair weather.

59. United States Weather Maps. From a single reading of the barometer it is impossible to make any accurate predictions concerning weather conditions. By observing successive readings of the barometer, however, some success in forecasting may be attained. But to get results that are of real value, one must study the readings of a number of barometers scattered over a wide area. The United States Government has observers stationed at various points throughout the United States. Reports taken simultaneously are telegraphed to central stations, where weather maps are prepared as follows: On a blank map of the United States heavy lines called *isobars* are drawn through places that report the same barometric pressure. Dotted lines called *isotherms* are drawn through places having the same temperature. Arrows are used to indicate the direction of the winds. Precipitation is shown by shading or by the use

of letters in the circles at the ends of the arrows. These circles are also shaded to show clouded skies.

The isotherms run in a general East and West direction, but the isobars form curves around "high pressure areas" and "low pressure areas." From the map shown in Fig. 69, we see that Northern Illinois is the center of a "low"

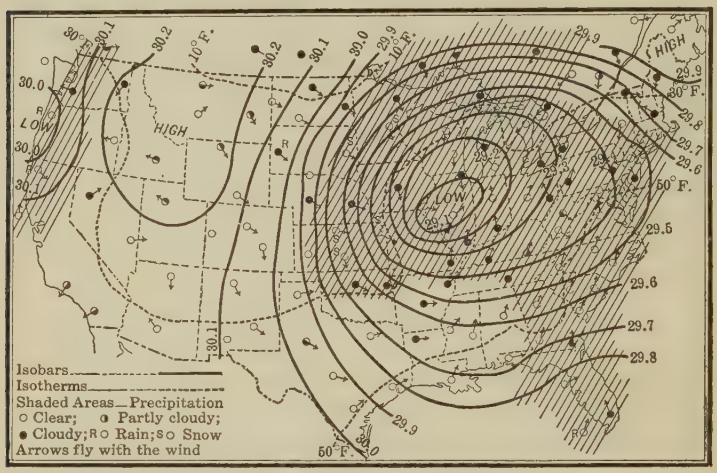


FIG. 69. — Weather Map of United States.

barometer area. Just as water flows from high pressure to low pressure, or runs down hill, so winds blow from regions of high barometric pressure to low pressure areas. In general, *winds blow toward the centers of low pressure areas, but the rotation of the earth on its axis deflects the winds so that the storm has a rotary motion.* Low pressure storms are called *cyclones*, but this word does not have the same meaning as "tornado." The winds in such *cyclonic* storms blow in a *counter-clockwise* direction in the northern hemisphere. *They are accompanied by cloudy weather, with rain or snow, and temperatures somewhat above normal.*

From areas of high pressure, like that shown around

Montana, the general direction of the winds is outward. On account of the rotation of the earth, this outward motion is rotary, but *clockwise* in the northern hemisphere. Such storms are known as *anti-cyclones.* They are generally *accompanied by fair or clear weather, with temperatures below normal.*

From long periods of observation, several facts concerning these storms have been learned: (1) Cyclonic and anti-cyclonic storms travel in an easterly direction across the United States in fairly well-defined paths; (2) their velocity is from 400 to 700 mi. in 24 hr.; (3) as they pass successively over places, they bring with them the characteristic weather conditions already noted; (4) cyclonic and anti-cyclonic storms succeed one another at two- or three-day intervals; (5) they are from 500 to 1500 miles in diameter. Thus, a trained observer at a central station with all the data before him can make a fairly accurate estimate of the weather conditions to be expected. Storms are predicted for 24 hr., or in some cases 48 hr., in advance. Almanac forecasts for weather conditions for months in advance have no scientific value.

60. Height of the Atmosphere. Just how high the atmosphere extends nobody knows. At an elevation of three miles the atmospheric pressure is only about one half as great as at sea level. September 28, 1921, Lieutenant Macready ascended in an airplane at Dayton, Ohio, to a height of 37,800 feet. At such altitudes the air is too rare to support respiration, and aviators must carry oxygen tanks. Lieutenant Macready's fur suit was electrically heated, since the temperature falls to about -70° F. It was necessary to supply the engine with compressed air to keep it working properly. This altitude record was broken on July 25, 1925 by Lieut. C. C. Champion, who ascended to a height of 38,474 feet. Self-registering instruments have been carried in small balloons to a height of nearly

22 miles. At high altitudes the balloons burst and release the instruments, which are protected by parachutes against injury from rapid fall.

From the darkening of the moon by the earth's atmosphere at the beginning of an eclipse, from the height of the aurora borealis, and from observations of the height at which meteors entering our atmosphere begin to glow, it is estimated that rarefied portions of the atmosphere extend to a height of from 125 to 500 miles.

QUESTIONS

1. How would you prove that air has weight?

2. How would you prove that air exerts pressure?

FIG. 70. — Fountain in vacuum.

3. Why must a mercurial barometer be hung in a vertical position? What would be the effect of inclining such a barometer?

4. Explain why hollow bodies are not crushed by the pressure of the atmosphere.

5. Suppose a little moisture is introduced into the space above the mercury in a barometric tube. How will the reading be affected?

6. If a little air is introduced into the space above the mercury in a barometric tube, how is the reading affected?

7. What would happen if a small pin-hole were made in the top of the tube of a barometer?

8. Exhaust the air from a bottle fitted with a stopcock, as shown in Fig. 70. When the end of the tube is held under water and the stopcock opened, water flows rapidly into the bottle. Explain.

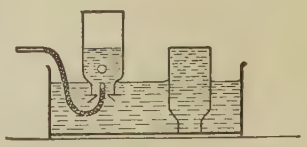


FIG. 71. — Gases are often collected by water displacement.

9. Fill a bottle with water, cover it with a glass plate, and invert it in water. (See Fig. 71.) Why does not the water flow out when the glass plate is removed? Put one end of a glass tube under the mouth of the bottle and blow through the tube. Why does the air

rise in the bottle? How is the water forced out of the bottle? Gases are often collected in this manner, the method being known as "water displacement."

10. The inkwell shown in Fig. 72 is filled when it stands in the position shown at *A*. Why does not the ink flow out when the inkwell is in the position shown at *B*?

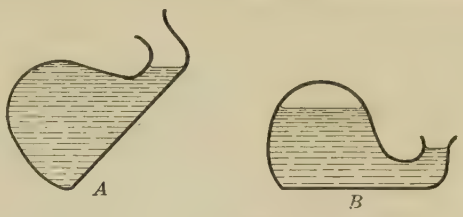


FIG. 72. — Pneumatic ink-well.

11. Liquids do not flow readily from a tap at the end of a barrel unless the bung is removed. Explain.

12. A person wishing to pour condensed milk from a can usually punches two holes in the top, at opposite sides. Why is the second hole necessary?

13. The cap of a fountain pen usually has one or more holes in it. Explain their purpose.

14. Pipettes are used in measuring liquids. As the air is sucked out of the pipette when its tip is beneath the surface of the liquid, the liquid rises in the pipette. Explain. If a finger is held tightly over the top, the liquid does not flow out even when the tip is raised above the surface. Explain. (See Fig. 73.)

FIG. 73. — Pipette.

15. Compare the action of a pipette with that of a medicine dropper or fountain-pen filler.

16. The first barometer constructed was a water barometer. The bowl was in the cellar and the tube extended up through the house above the roof. A wooden figure floating on the water rose above the roof in fair weather and retreated into the attic in foul weather. The owner was quite successful in forecasting the weather and was compelled to destroy his barometer because his neighbors accused him of wizardry. State the advantages of a water barometer and also give its defects.

17. A few years ago some workmen used steam to clean the in-

terior of a tank-car. The opening was then tightly closed. A few minutes later, the steel car collapsed. Explain.

18. State two reasons why mercury is suitable for use in barometers.

19. What is the difference between "fair" and "clear" as used in weather forecasts?

20. A high percentage of the time the weather forecaster is correct in his predictions. Why does he fail in some cases?

21. The cap on the gasoline tank of an automobile always has a small hole in it. What is it for, and what would be the effect of closing it?

22. In the cylinders of an automobile, the piston produces a partial vacuum as it moves downward. How does the gasoline vapor get into the cylinder?

23. Does the diameter of a Torricellian tube have any effect upon the height to which the mercury rises? Explain.

24. How does the air get into your lungs in ordinary breathing?

PROBLEMS

1. Find the weight of the air in a room 40 ft. long, 30 ft. wide, and 16 ft. high.

2. A barometer at the base of a cliff reads 29.8 in. At the top of the cliff it reads 27.1 in. What is the height of the cliff?

3. If a barometer is sunk in water until the surface of the mercury in the bowl is 27.2 in. below the surface of the water, how would the reading of the barometer be affected?

4. A pair of Magdeburg hemispheres has a diameter of 3.5 in. If a perfect vacuum can be obtained, what force is needed to pull them apart? (Hint. Calculate the pressure of the air on a circle 3.5 in. in diameter.)

5. The Magdeburg hemispheres used by Otto von Guericke were 22 in. in diameter. What force was needed to separate them?

6. The palm of your hand probably has about 12 sq. in. of surface. How much force would be needed to hold your hand palm upward if the air beneath your hand were removed?

7. If the liquid used for a barometer is gasoline, sp. wt. $=0.7$, how long a tube is needed, provided a 33 in. tube is used for a mercury barometer?

B. COMPRESSIBILITY AND EXPANSIBILITY OF GASES

61. Expansibility of Gases. If we put a pint of liquid in a quart bottle, the liquid does not expand and fill the bottle. On the other hand, if we puncture an inflated tire, the air inside expands and takes up decidedly more room than the same volume had occupied. The space a gas occupies depends upon the pressure to which it is subjected. A half-inflated rubber ball under a bell-jar expands as the air is pumped out of the jar, since the pressure of the air on the outside is reduced. (See Fig. 74.) If we let the air back into the jar, the ball is again reduced in size, showing that the gas is perfectly elastic.

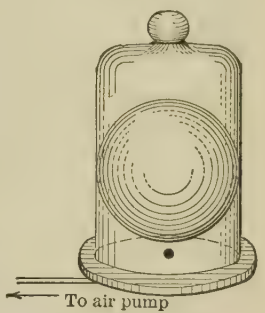


FIG. 74. — Gases expand when pressure upon them is decreased.

62. Standard Temperature and Pressure. While the volumes of both solids and liquids are to some extent affected by changes in temperature and pressure, yet it is unnecessary to read the thermometer and barometer in making ordinary measurements. The carpenter does not bother to read the thermometer when he cuts a piece of lumber of a certain length, because the variation in length is negligible for ordinary work. But when greater accuracy is required, both temperature and pressure corrections become necessary in the measuring of solids and liquids. For example, the standard meter is *exactly one meter* in length *when the temperature is 0° C.*

For measuring gas volumes, which vary so much, it is *always* necessary to consider both the temperature and the pressure to which they are subjected. To prevent confusion, 0° C. is used as *standard temperature.* The pressure exerted by a column of mercury 760 mm., or 76 cm., high is accepted as *standard pressure.* The abbreviation S.T.P. is

often used to indicate standard temperature and pressure. For example, when we speak of a gas having a volume of 1000 c.c. at S.T.P., we mean that it would occupy that volume when the temperature is 0° C., and the pressure upon it is equal to that of one atmosphere, or 76 cm. of mercury. At a different temperature or pressure, it will have a decidedly different volume.

63. Incompressibility of Liquids. While gases are very compressible, liquids are almost incompressible. Water, for example, is so nearly incompressible that the stupendous pressure of 20 tons upon one cubic inch is required to reduce its volume by only 0.1. This means that the water at the bottom of the ocean is compressed very little by the weight of the waters above. Water at the bottom of the ocean is not much denser than water at the surface. We have already learned that the air at sea level is much denser than the air on top of a high mountain. The greater density of air at sea level is due to its compression by the weight of the upper layers of air which it sustains.

64. Boyle's Law. Robert Boyle was the first to make a *quantitative* study of the effect of pressure on gas volumes. Undoubtedly many people were familiar with compressed air, but no one had taken the trouble to investigate how many pounds pressure it takes to reduce the volume of a gas to one half or to one third. A tire is pumped up to a pressure of 44 lb. per sq. in. When a "blow-out" occurs, and the pressure is reduced to that of one atmosphere, 14.7 lb. per sq. in., how many drivers ever stop to inquire how much the volume of the air in the tire increased during the "blow-out"?

Boyle used a J-shaped tube to study the relationship between volumes and pressures. When the tube contains a little mercury, as shown in Fig. 75*A*, the volume of air, V, in the short arm of the tube can be measured. Since the level of the mercury in both arms is the same, we know

that the pressure, P, at the surface of the mercury in the open tube is equal to that of the air at that particular place. By reading a barometer, its exact value can be determined. Now if we pour a little mercury into the open end, we add to the pressure and the volume grows less. We next measure the new volume, V', as shown in Fig. 75*B*. We find the new pressure, P', by adding to the barometer reading the difference in the lengths of the mercury columns in the open and closed arms of the tube. Boyle found that increasing the pressure reduced the volume correspondingly. Doubling the pressure reduced the volume to one half; trebling the pressure reduced the volume to one third. BOYLE'S LAW may be stated as follows: *The volume of any dry gas, the temperature remaining constant, varies inversely with the pressure sustained by it.*

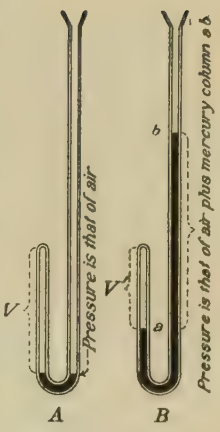


FIG. 75. — Boyle's law tubes.

65. Boyle's Law Shown Graphically. Suppose we start with 2000 c.c. of gas measured at a pressure of 200 mm. of mercury. By experiment, it may be shown that if we subject this volume of gas to the successive pressures given along the margin of Fig. 76, its volume, V, will be

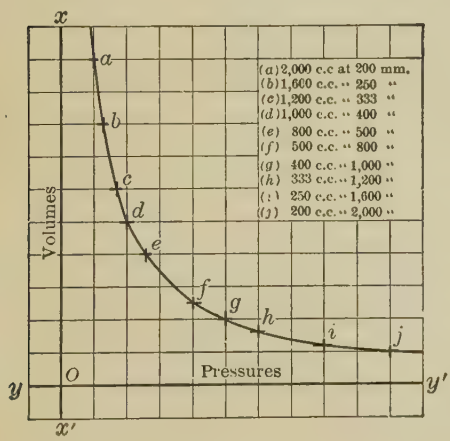


FIG. 76. — Curve of inverse proportion.

reduced to the amount shown opposite the corresponding pressure, P. Using the pressures as abscissas and the volumes as ordinates, we obtain an *inverse* proportion graph. Since one factor increases as the other decreases, *the product of the volume and its corresponding pressure is always a constant quantity.* Stated algebraically, VP = a constant. In all cases, $VP = V'P'$. V' represents the *new* volume, and P' the *new* pressure.

66. Effect of Pressure on Gas Densities. Since there is no change in the weight of the gas during the changes in volume given in the preceding section, evidently *the density of a gas increases in direct proportion to the pressure it sustains.* A liter of air weighs 1.29 gm. at a pressure of one atmosphere, but a liter vessel can hold 5.16 gm. of air under a pressure of four atmospheres. In the latter case, the air is four times as dense.

PROBLEM. Given 500 c.c. of gas under a pressure of 750 mm. of mercury. What volume will the gas occupy at a pressure of 800 mm.? If this gas has a density of 1.5 gm. per liter under the original pressure, what will be its density under the new pressure?

Solution. Since the pressure is increased, the volume will be reduced. The new volume will be $\frac{750}{800}$ of the original volume. $\frac{750}{800}$ of 500 c.c. = 468.8 c.c. Or, $VP = V'P'$. Then, $500 \times 750 = V' \times 800$. Whence, $V' = 468.8$ c.c.

Since the pressure is increased, the density will be increased. The new density will be $\frac{800}{750}$ of the original density. $\frac{800}{750} \times 1.5$ gm./liter = 1.6 gm./liter.

67. The Vacuum Pump. A pump used to exhaust the air from vessels was invented by Otto von Guericke in 1650. Such a pump consists of a cylinder, a piston, and valves. By means of a rod, the piston can be moved up or down the cylinder. This piston should fit the cylinder so tightly that air cannot pass.

By reference to Fig. 77 we can understand how such a

pump operates. As the piston P is pulled up the cylinder C, the valve V_2 being closed, the air above the piston is forced out through a small hole in the top of the cylinder. The air in the bell-jar B expands and part of it flows through the valve V_1 into the partial vacuum which was just pro-

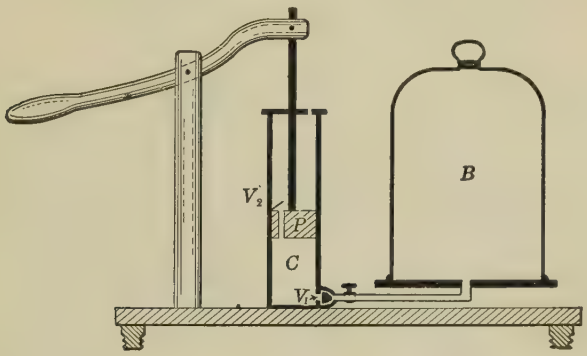


FIG. 77. — Exhaust air pump.

duced in the lower part of cylinder C. Like a traffic policeman at the exit to a one-way street, the valve V_1 lets the air flow from the bell-jar into the cylinder, but it does not let the air flow from the cylinder back into the bell-jar. During the downstroke of the piston, this valve closes. Since the air cannot go back into the bell-jar, it forces its way up through valve V_2 into the space above the piston. On the next upstroke of the piston, the air in the upper part of the cylinder is pushed out, and more air from B flows over into the lower part of the cylinder.

Suppose the cylinder and the bell-jar are both of the same size, one half the air will flow into the cylinder during the upward stroke of the piston, and one half of the air will be removed at the completion of one stroke of the pump. During the next complete stroke one half of the remaining air or one fourth of the original amount. is removed. The next

stroke removes one half of what remains, or one eighth of the original amount. The action continues thus until the expansive force of the air finally becomes too weak to operate the valves of the pump.

68. The Aspirator. A suction pump, or aspirator, is often used in the laboratory to produce a partial vacuum. It is screwed to a water faucet, and the vessel to be evacuated is attached to the tube on the side of the pump. (See Fig. 78.) As a current of water flows rapidly through the inner tube, it drags along with it air molecules from the vessel to be exhausted. The air in the vessel expands and more molecules are carried away by the running water. In this manner quite a good vacuum can be produced in a short time.

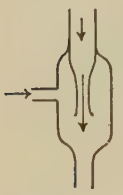


FIG. 78. — Aspirator.

69. Ejectors and Injectors. When the wind blows across the top of a chimney, the rapidly moving current of air carries along with it some of the gas molecules within the chimney. (See Fig. 79.) The gases within the chimney expand, and their density is decreased. For this reason a chimney draws much better on a windy day.

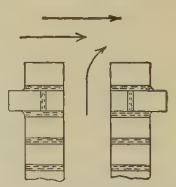


FIG. 79. — Ejector principle.

The *atomizer* is another example of the *ejector* principle. If we squeeze the bulb, Fig. 80, we force a current of air across the top of a small tube which dips down into the liquid in the atomizer. The air pressure in the tube is reduced, and some of the liquid is pushed up the tube by the expansive force of the air in the bottle. As the liquid reaches the tip of the tube, it is broken up into a fine spray by the current of air.

FIG. 80. — Atomizer.

The *injector*, which is sometimes used instead of a pump for filling steam boilers, does not differ in principle from the

ejector. A blast of steam at high velocity flows through a jet surrounded by a nozzle. As the steam passes through the nozzle, it carries water with it through a check valve into the boiler.

70. Uses of the Exhaust Pump. Some type of exhaust pump is used whenever it is necessary to remove a part or all of the air from a container. Unless the air is removed from an electric light bulb, the filament will burn. In some types

FIG. 81. — An exhaust pump is attached to the pipe line along the wall. From this line tubes lead to the can which is connected by tubes with the cow's udder.

the bulb is then refilled with a gas which has no effect upon the filament. In making X-ray bulbs, radio tubes, and thermos bottles, an exhaust pump is used. The milking machine of Fig. 81 is a common application of the vacuum pump.

Liquids evaporate much more rapidly in a partial vacuum than they do under ordinary atmospheric pressure. In drying foods, or dehydrating them, *vacuum* pans are used to hasten the drying. Crystals, dye-stuffs, etc., are sometimes dried in a vacuum pan. In sugar refineries, vacuum pans are used during the evaporation of the sugar solution, since

the syrup boils at a lower temperature in a vacuum, and danger of scorching is avoided. (See Fig. 82.)

The *vacuum cleaner* also furnishes a practical application of the exhaust pump or exhaust fan. In the latter case, a fan is driven by an electric motor. The fan pushes the

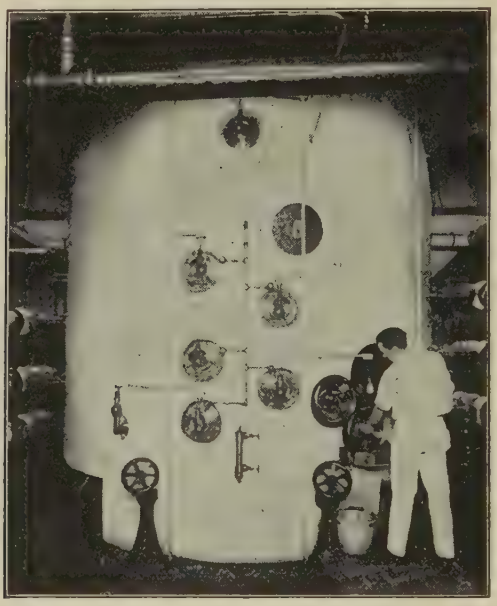


FIG. 82. — Vacuum pan for making granulated sugar.

air away in front of the blades, and leaves a partial vacuum on the other side of the fan. As the air rushes in through the mouthpiece of the tube leading to the fan chamber, it carries with it the dust particles from the article that is being cleaned. A rotary brush is sometimes used to sweep and beat the rug or carpet at the same time in order to loosen the dirt. (See Fig. 83.)

71. The Compression Pump. The bicycle pump, or automobile tire pump, furnishes a common example of compression

pump. Such pumps are used to push or crowd more air into a container. In one of the simple types, shown in Fig. 84, a leather disc attached to the piston permits the air to flow past it in one direction, but not in the other. Hence it takes the place of a valve in the piston. The other valve may be placed in the outlet tube; with pneumatic tires a valve is placed in the valve stem of the tire itself.

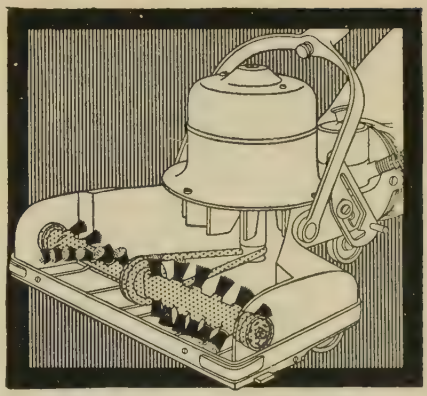


FIG. 83. — The revolving brush beats the rug gently and the dirt is pushed into the vacuum produced by the motor.

Fig. 85 shows the construction of one type of compression pump. The piston has no valves, and fits the cylinder so tightly that air cannot

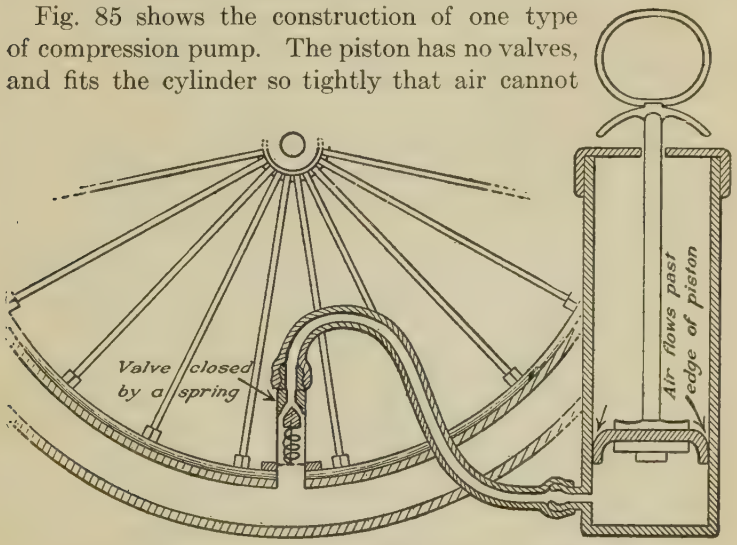


FIG. 84. — Simple compression pump used to inflate tire.

pass. The valves are so arranged that air enters through one as it leaves through the other. On the upstroke of the piston the air above it is pushed out of the cylinder. Valve V_1 opens and lets the air from container A expand into the cylinder. On the downstroke this valve closes and valve V_2 opens as the piston pushes the air out of the lower part of the cylinder.

Such a pump may also be used as an exhaust pump. It will pump air out of one vessel into another. A vessel attached at A is exhausted as the pump operates, while compression occurs in the container attached at B. Thus a reversal of the direction in which the valves open converts a compression pump into an exhaust pump.

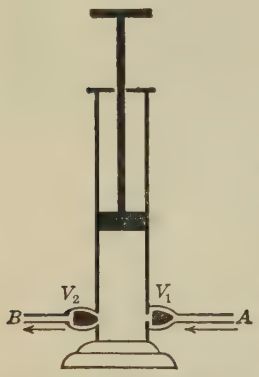


FIG. 85. — Compression air-pump.

72. Uses of Compression Pumps. Air compressed under a pressure of several atmospheres exerts a tremendous expansive force. Hence it may be used for driving certain types of machines. It is especially satisfactory, since strong-walled tubes can be used to transmit this pressure wherever needed.

(*a*) *Pneumatic tires.* Compressed air finds extensive use in pneumatic tires. In these cases it forms an elastic cushion to absorb shocks on rough roads. We observe that Pascal's law applies to gases. As pressure is applied to the air in the valve stem, this pressure is transmitted equally to all parts of the tire. When a tire is inflated to 44.1 lb. pressure per sq. in. (3×14.7 lb.) it contains three times as much air as it would under ordinary atmospheric pressure.

(*b*) *The Westinghouse air brake.* The flanged wheel, invented by Stevens, and the air brake, invented by Westinghouse, have made it safe to drive trains at high speed. After

Westinghouse conceived the idea of a brake which could be applied by the engineer to all the cars at the same time, he could not think of a satisfactory fluid to operate the brakes. Learning that compressed air was being used to operate some of the tools used in tunnel construction work in Europe, he decided to try compressed air for his brakes. The almost universal use of the air brake for trains and trolley cars shows that his test was successful.

The air brake may be operated directly from the engine or it may operate automatically from an auxiliary reservoir of compressed air stored under the car itself. In Fig. 86, P is a pipe connected with the main reservoir on the engine, in which a compressor maintains a pressure of about five atmospheres. The reservoir R communicates with P through a triple valve V. This valve maintains communication between P and R and shuts out the air from C, as long as the pressure from the engine is supplied to P. When this pressure is diminished, either intentionally by the engineer or accidentally by the breaking of the coupling D, the valve opens in such a way that air from the reservoir R flows into C and forces the brake piston to the left, thus setting the brakeshoes against the wheels. Readmission of air through P lets the air in C escape and the spring S releases the brakes.

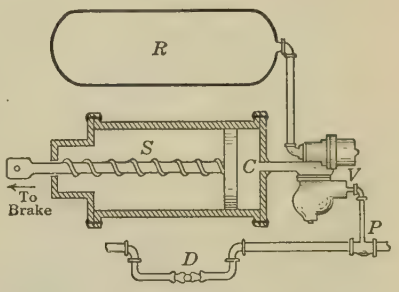


FIG. 86. — Westinghouse air brake.

(*c*) *Diving bells and diving suits.* If we force a tumbler under water, mouth downward, the pressure of the water compresses the air in the tumbler to some extent, the amount of compression depending upon the depth. The air in a *diving bell* is compressed in a similar manner as it is lowered

FIG. 87. — Diving bell being lowered.

in the water. (See Fig. 87.) In the modern diving bell the workmen are supplied with air forced down through a tube connected with a compressor at the surface. The air is supplied fast enough to force all the water out of the bell and keep a stream of bubbles flowing out from its lower edges. (See Fig. 88.)

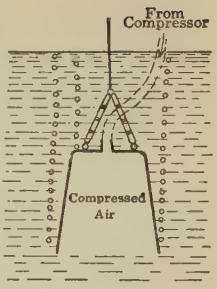


FIG. 88. — Diving bell supplied with compressed air.

The *diving suit* is sometimes supplied with compressed air in the same manner as the diving bell. In other cases the diver has a self-contained apparatus and is independent

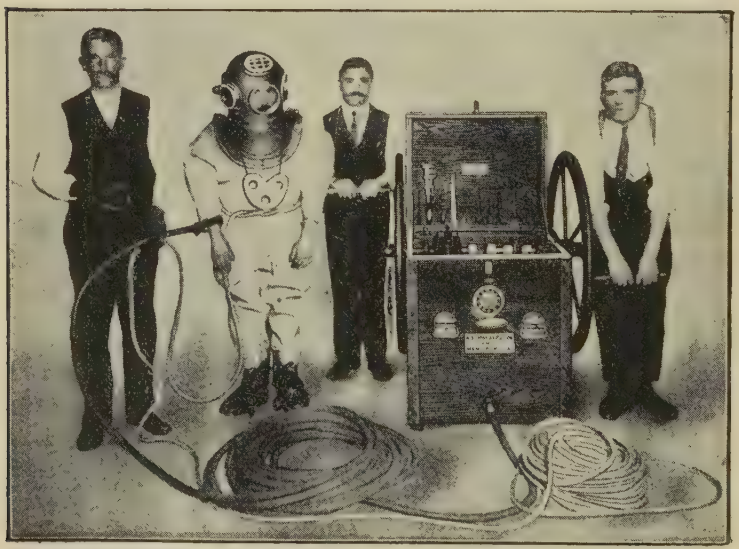


FIG. 89. — Diver equipped with helmet, suit, and weighted shoes. Compressor used to supply diver with air.

of a compressed air supply line. He carries a tank of compressed air. By opening a valve he permits air to escape just fast enough to keep his suit filled with air. A constant stream of bubbles passes out through a valve in his suit. (See Fig. 89.)

(*d*) The *pneumatic caisson* is used for constructing bridge piers or foundations under water. The caisson is open at the lower end and it is weighted so it will sink, not only in water, but also into the mud at the bottom. (See Fig. 90.) Compressed air is used to keep the water out of the caisson. The workmen enter the caisson through air locks, or air-tight doors, and material is passed down to them in the same manner. Thus the foundation may be built inside the caisson.

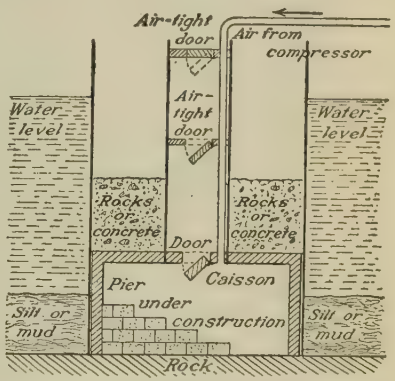


FIG. 90. — Diagram to show operation of pneumatic caisson.

For tunnel construction jacks are used to push forward a cylindrical shield as the material is removed by workmen. (See Fig. 91.) The tunnel lining is constructed inside the shield. A bulkhead of concrete is built to separate the high compression chamber at the left from the chamber at the right.

(*e*) *Pneumatic despatch.* In some large buildings compressed air is used for transmitting cash boxes and small packages. It has also been used for transmitting mail between the post office and the railroad stations, although the system threatens to yield to the motor truck. The cylindrical carrier, which is slightly smaller than the tube, has packing rings near the ends to make it fit the tube fairly tightly with-

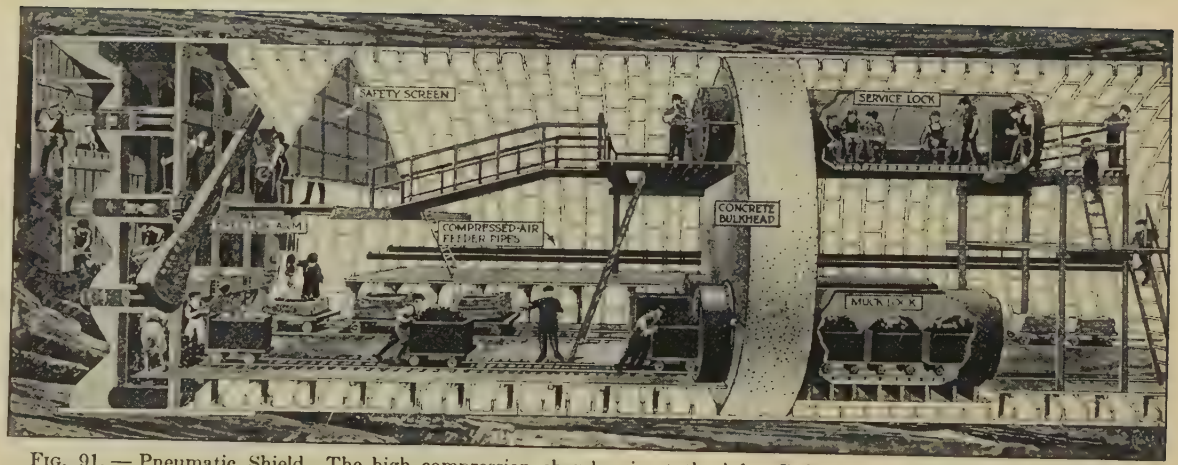


FIG. 91. — Pneumatic Shield. The high compression chamber is at the left. Before men enter it, they first remain a few minutes in the service lock, where the air pressure upon them is gradually increased. More air is thus dissolved in the blood. Unless "decompressing" is done gradually, the men will suffer as the excess air accumulates in the blood vessels. It should escape slowly through the lungs. Helium is now sometimes used in the service lock. It is not nearly so soluble in the blood as nitrogen, and it escapes much more rapidly by diffusion. Thus the time required for "decompressing" the men is reduced to about one-fourth. Thus the dangers from an excess of nitrogen in the blood are reduced. The cars containing the excavated material are removed through the muck lock. (*Courtesy of Popular Science Monthly.*)

out much friction. An exhaust pump at the receiving end and a compression pump at the transmitting end of the tube

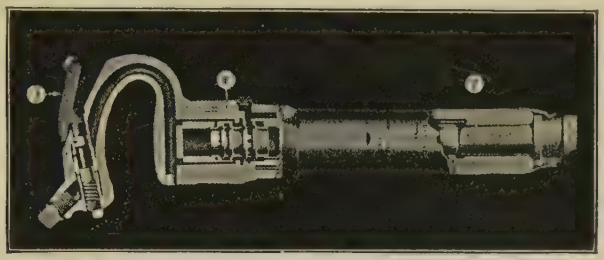


FIG. 92. — Pneumatic riveter. (1) Valve controlling air; (2) hammer; (3) trigger.

produce a difference of pressure that is sufficient to drive the carrier through the tube with considerable speed.

(*f*) *Other uses for compressed air.* Many tools are operated

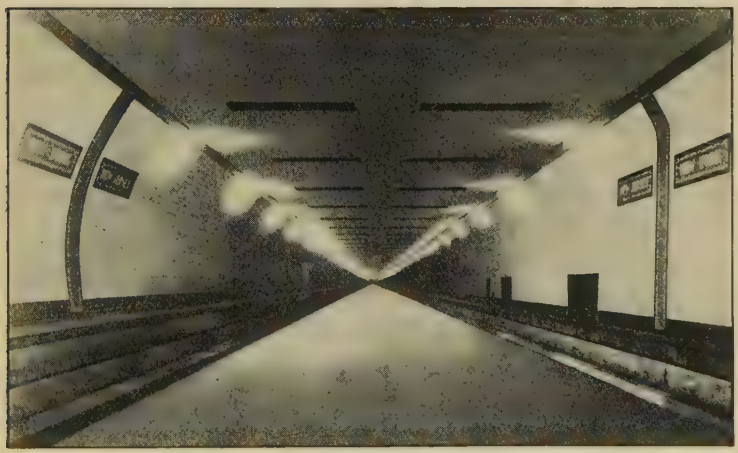


FIG. 93. — Inside view of the Holland tunnel for vehicular traffic.

by compressed air. The list includes *riveting hammers, rock-drills, the sand blast for cutting and polishing,* and *some rotary tools.* (See Fig. 92.) The *bellows* are used to produce

a forced draft for making a blacksmith's forge hotter, or to supply compressed air for organ pipes. They are indirectly used to produce the partial vacuum needed for the operation of player pianos.

Mines and large buildings are often ventilated by compressed air. It is used to operate car doors and for various regulating devices. In submarines it is used to force the water from the various chambers, and it operates the propellers which drive torpedoes.

73. The Holland Tunnel. A tunnel 9250 ft. in length was recently opened between New York City and Jersey City, New Jersey. More than one mile, 5480 ft. of this tunnel, which is for vehicular traffic, is built under water. The two tunnels, each 29 ft. 6 in. in diameter, lie side by side in the mud under the Hudson River. These tunnels are expected to provide a roadway for as many as 2000 automobiles per hour. Fig. 93 shows the appearance of the tunnel.

FIG. 94. — Cross-section of the Holland tunnel.

The problem of ventilating these tunnels was quite as difficult as that of constructing them. Two ventilating buildings at either end were constructed to supply compressed air to remove the dangerous carbon monoxide which comes from the exhaust of all automobiles. In each one there are 21 large electric fans, part of them used to compress air, which then enters the tunnel near the bottom; and part of them for exhausting the air from the ducts at the top. Although these compressors can force 1,900,000 cu. ft. of air into the tunnels per minute, there is no longitudinal draft in the tunnel. The air rises to the exhaust ducts directly. (See Fig. 94.)

QUESTIONS

1. Is air suitable for use in a hydraulic press? Explain.

2. Theoretically, can a perfect vacuum be produced with a pump of the type described in § 67?

3. What advantages do air brakes have over the older hand brakes?

4. What is meant by the expression "pressure of one atmosphere"?

5. Distinguish between "direct proportion" and "inverse proportion."

6. When a ship sinks in water, does it go to the bottom, or does it stop part way down, as some people believe? Explain.

7. Why does a chimney draw better on a windy day? Why should the top of a chimney be as high as the highest part of the roof?

8. What are the advantages in the use of compressed air for transmitting power?

9. With a train fitted with air brakes, what happens if one car breaks loose from the train?

10. Is the fuel gas that is supplied to your gas burner under a pressure of more or less than one atmosphere?

FIG. 95. — Blowing into flask compresses air.

11. Blow through the jet tube of Fig. 95 as hard as you can. Explain the results.

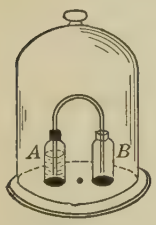


FIG. 96. — Bacchus' experiment.

12. Does it indicate high or low atmospheric pressure when smoke rises vertically from a chimney? Is there truth in the old saying, "It is a sign of rain when the smoke falls to the ground"?

13. Two small bottles are placed under a bell-jar. (See Fig. 96.) *A* is *partly* full of liquid and is tightly stoppered. When the air is pumped out of the bell-jar the liquid flows through the bent tube into *B*. It flows back again when the air is readmitted. Explain. Repeat the experiment, having *A full* of the liquid. Explain.

14. A tire-gauge is made to read zero when the pressure is one atmosphere. A tire is inflated at sea level until it shows a pressure

of 40 lb. per sq. in. The same tire is inflated at the top of Pike's Peak until it shows 40 lb. pressure with the same gauge. Is the tire tighter or looser than at sea level?

15. Lawn rollers are often hollow steel shells. Water is added to give the desired weight. Suppose you tried to fill such a roller by screwing the end of a garden hose into the threaded opening in the end of the roller, and turning on the water. What would probably happen? Explain.

16. A man needs a certain number of grams of oxygen daily. Why must he breathe more frequently or more deeply at the top of a mountain than at sea level? Breathing mountain air exercises the lungs, and it is thus beneficial for consumptives.

PROBLEMS

1. Suppose the piston of an air brake has a diameter of 6 in. What force acts to set the brakes if the air in the reservoir is under a pressure of five atmospheres? (Consider the effective pressure equal to four atmospheres. Why?)

2. A diver is submerged to a depth of 170 ft. To what total pressure, both atmospheric and liquid, is he subjected? How will the volume of a bubble of gas be affected as it rises from his suit to the surface of the water?

3. What will be the weight of one liter of air in a tire that is inflated under a pressure of five atmospheres?

4. The volume of a gas is 1400 c.c. when the barometer reading is 825 mm. What volume will the gas occupy when the barometer reading is 645 mm.?

5. Suppose you have 200 cu. ft. of oxygen gas under a pressure of one atmosphere. What pressure would be needed to crowd all this gas into a container whose volume is 10 cu. ft.?

6. An automobile tire contains 800 cu. in. of air at an absolute pressure of 58.8 lb. per sq. in. What volume will this air occupy after a "blow-out"?

7. Given 1500 c.c. of gas measured at a pressure of 660 mm. of mercury. What pressure in mm. of mercury will be needed to reduce the volume of the gas to 1000 c.c.? To what is this pressure equivalent in lb. per sq. in.?

8. If ordinary air were subjected to a pressure of 1000 atmos-

pheres how would its density compare with that of water? Do you think a block of wood would float in such air?

9. A tire has a volume of 900 cu. in. When inflated, a tire gauge shows a reading of 73.5 lb. per sq. in. What volume would the air occupy at a pressure of one atmosphere? (Remember that the tire gauge reads zero at a pressure of one atmosphere.)

C. OTHER PNEUMATIC APPLIANCES

74. The Lift Pump. For use in cisterns and in shallow wells, the *lift* or *suction*, pump, is in common use. In construction, the water pump differs little from the air pump. The cylinder, which generally rests on a platform at the surface of the ground, is connected with a pipe which extends down into the well. (See Fig. 97.) A piston P may be moved up or down the cylinder C by means of the pump-handle. Two valves are used, one in the piston, and the other in the lower part of the cylinder.

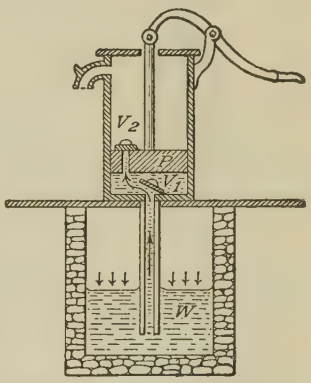


FIG. 97. — Diagram of lift or suction pump.

As the piston moves upward valve V_2 is closed. The air above the upward moving piston is pushed out of the cylinder, leaving a partial vacuum beneath the piston. The downward pressure of the air upon the surface of the water in the well pushes some water up the pipe and into the cylinder. As the piston moves downward, the valve V_1 closes to prevent the water from flowing back into the well. But the water that had been pushed up into the cylinder will now flow through valve V_2 to occupy part of the space above the piston. The next upward stroke lifts some of the water to the spout, while more is pushed into the cylinder by the pressure of the air on the water surface.

Since the atmospheric pressure is great enough at sea level to balance a column of water just 34 ft. high, the suction pump cannot be used if the cylinder stands more than 34 ft. above the surface of the water. We have already learned that the pump used by the Duke of Tuscany would not lift water more than 32 ft. In practice, the height to which water is raised by such a pump is not more than 28 ft., since the leakage of the valves and the piston makes it difficult to secure a good vacuum.

75. The Force Pump. By the use of a long piston rod and outlet pipe, the cylinder of a force pump may be placed in a deep well near the surface of the water. The pressure of the air lifts the water up to the cylinder, and the muscular exertion of the man who operates the pump *forces* the water up to the pump-spout above ground. Hence the name *force pump.*

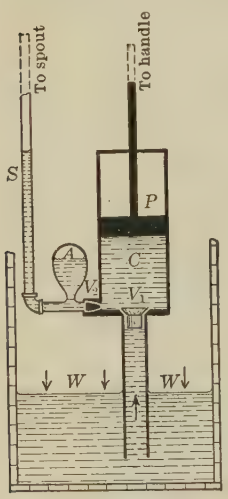


FIG. 98. — Force pump (for deep wells).

In construction, the force pump differs from the lift pump in two respects: (1) The piston is solid and fits the cylinder so tightly that water cannot pass; (2) Valve V_2 is not in the piston, but at the entrance to the outlet pipe near the bottom of the cylinder. (See Fig. 98.) During the upward stroke of the piston, a partial vacuum is produced in the lower part of the cylinder and inlet pipe in just the same manner as with the lift pump. Water is forced up into this partial vacuum by the air pressure. During the downstroke valve V_1 closes and the water is *forced* into the outlet pipe S. The valve V_2 is necessary to keep the water from flowing back into the cylinder during the next upstroke of the piston. The student will find the valve arrangement

easy if he remembers that the valves must open in the direction one wishes the liquid to flow, and that they open alternately.

Unless an air-dome is used, the water from a force pump will come in spurts during the downstroke *only*. When the air-dome is used, some water is forced into the dome during each downstroke, thus compressing the air in the dome. But this compressed air expands again during the next upstroke and pushes some of the water up the spout. Thus the dome causes a continuous flow of water.

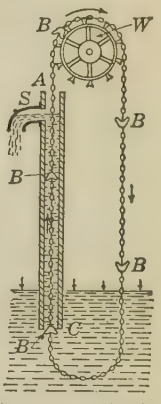


FIG. 99. — Chain pump.

76. The Chain Pump. We have represented in Fig. 99 an inexpensive, efficient pump widely used in country sections for shallow wells and cisterns. AC is a tube about $1\frac{1}{2}$ inches in diameter. When the ratchet wheel W is turned by a crank, a continuous chain is pulled up through the tube and lowered into the well on the other side of the wheel. Rubber buckets B which fit the pump tube air-tight are inserted in the chain at intervals of 6 or 8 ft. As a rubber bucket is pulled up through the pump-stock AC it removes the air, and the water follows, being lifted to the spout partially by atmospheric pressure and partially by the bucket that follows.

77. The Siphon. Quite often it is desirable to transfer liquids from barrels or heavy containers to other vessels without lifting the heavy containers, or incurring the risk of spilling the liquid in trying to pour it from a large container. A bent tube, having arms of unequal length, may be used to transfer liquids over an elevation from one container to another of lower level. A tube, generally made of rubber or glass, used for such purpose is called a *siphon*.

Suppose the tube $ABCD$ is filled with water and its ends

placed in the vessels of water S and S', Fig. 100. If the pressure on the surface of the water at S is greater than the pressure at S', the water will flow through the tube in the direction shown by the arrow. Of course the converse is true. The pressure at S is the pressure of one atmosphere, less the backward pressure of the column of water AB. The pressure at S' is the pressure of one atmosphere, less the backward pressure of the column of water CD. But the atmospheric pressure on the surface of the water at S' is reduced the more, since the column of liquid CD is longer than the column AB by DE. Thus the *effective* pressure of the atmosphere at S becomes greater than at S', and the liquid flows up over the elevation and down into the lower vessel.

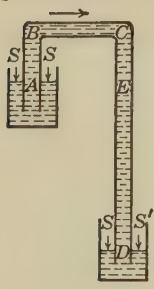


FIG. 100. — Siphon.

Since the difference of the water pressures in the two arms really causes the water in the siphon to flow, the rate at which it flows must increase as we increase the difference between the vertical lengths of the arms. If we increase the vertical length of DE the siphon will flow faster. If we reduce the length of this water column to zero, the siphon will cease to flow.

78. The Cartesian Diver. By careful adjustment it is possible to put into a small vial just enough water so that the slightest downward force applied to it, as it floats mouth downward in a cylinder of water, will submerge it. (See Fig. 101.) If a piece of sheet rubber is stretched over the cylinder and pressure applied to it gradually, the vial slowly descends, rising again when the pressure is removed. The Cartesian diver, or bottle imp, illustrates several principles of physics. Before the pressure is applied, the specific weight of the vial and contents is slightly less than that of water. The

FIG. 101. — Cartesian diver.

pressure applied is transmitted equally in all directions (Pascal's law), the air in the vial is compressed, and a little more water enters the vial, thus increasing its specific weight until it slowly sinks. When the pressure is removed, the expansion of the air in the vial forces out some of the water and the vial rises. The *diver* is an application of Pascal's law, Archimedes' principle, the laws of flotation, and the compressibility and expansibility of air (Boyle's law). The usual type is a toy devised by Descartes. It consists of a hollow imp-shaped figure with a small opening in the end of his tail for the entrance and exit of the water which changes his specific weight.

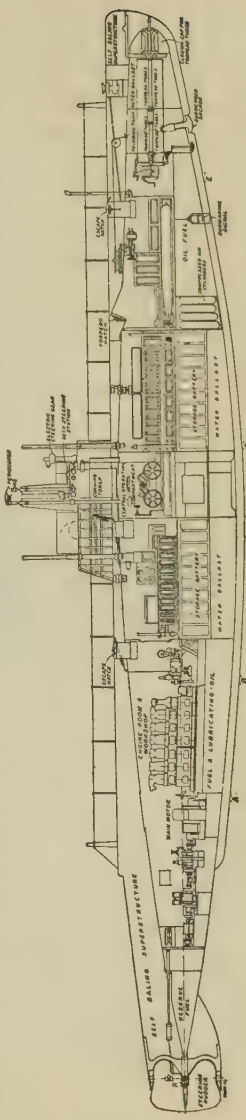


Fig. 102. — Diagram of a submarine.

79. The Submarine. The idea of using submarine vessels in warfare dates back at least to the time of Alexander the Great. During the Revolutionary War, David Bushnell made a submarine and tried to destroy some of the English vessels in New York harbor. But the submarines, which were developed to so high an efficiency during the World War, were modeled after the submarines of Lake and Holland, American inventors.

The principles used in the submarine are not unlike those used

in the Cartesian diver. When a submarine is traveling on the surface, it floats just as any other ship does. Before the boat is submerged, certain compartments are opened to fill them with water. Thus the boat sinks deeper in the water, until only the deck and conning tower are awash. In the act of submerging, the propellers drive the boat forward, and the diving rudders are set at such an angle that the boat is pushed under water. To bring the submarine to the surface again, the diving rudders are set at such an angle that the bow of the boat is pushed upward. Compressed air is used to force the water out of the flooded compartments. (See Fig. 102.)

80. Buoyancy of Gases. Clouds float in the air, and smoke is buoyed up by the weight of the air it displaces. Archi-

FIG. 103. — The *Los Angeles* lands on the airplane carrier *Saratoga*. (*Courtesy of Science and Invention.*)

medes' principle applies to all fluids, gases as well as liquids. Just as objects that do not float in water lose part of their weight when submerged, so objects that are heavier than air lose part of their weight when submerged in air. An object that displaces exactly one liter of air will weigh 1.293 gm. more in a vacuum than it does in air at S.T.P. In other words, the buoyancy of air is 1.293 gm. per liter. The laws of flotation apply to all gases, and an object will rise in air if the weight of the air it displaces is greater than its own weight. Fig. 103 shows the *Los Angeles*, which floats in air, alighting upon the *Saratoga*, which floats in water.

81. Balloons and Airships. A balloon consists essentially of a strong, air-tight bag filled with some gas lighter than air. It will rise if its weight plus the weight of the gas it contains is less than the weight of the air it displaces. If the balloon is filled with hydrogen, a gas which weighs only 0.09 gm. per liter, then every liter of air the balloon displaces exerts a lifting force equal to the difference between the weight of one liter of air and one liter of hydrogen. 1.29 gm. $-$ 0.09 gm. $=$ 1.2 gm. While it is the buoyant force of the air displaced that causes a balloon to rise, it is commonly spoken of as the *lifting force* of hydrogen. For example, the *so-called lifting force of hydrogen is 1.2 gm. per liter.* Since there are 1000 liters in a cubic meter, the lifting force of hydrogen is equal to 1200 gm. per cu. m. (See Fig. 104.)

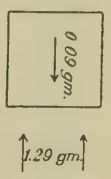


FIG. 104. — Hydrogen has lifting force of 1.2 gm. per liter.

Hydrogen is the lightest gas known, but it is very inflammable. Hence it is dangerous to use hydrogen in military balloons. *Helium* is twice as heavy as hydrogen, but it does not burn. Since its lifting force equals 1.29 gm. $-$ 0.18 gm., or 1.11 gm. per liter, we see that it is nearly 93% as efficient as hydrogen, and there is no danger from fire on account of its use. Its price before the war was about $1700 per quart. When its importance for military purposes was realized, a systematic search for a more abundant supply was begun. Engineers found that some of the natural gas in Texas and Oklahoma contains 1 or 2% of helium. In separating the helium, liquid air machines are used to cool and compress these gases. Everything liquefies but the helium, which may then be separated from the liquid. By this method, the price of helium has been reduced to about 4c. per quart. Helium is compressed in steel cylinders and shipped to Lakehurst, N. J., where it is used for filling dirigibles. After the *Los Angeles* arrived from Germany,

the hydrogen was removed from her gas bags and replaced with helium. (See Fig. 105.)

Airships, or *dirigibles*, are balloons fitted with steering devices and propellers. Gasoline engines aggregating 3000

Fig. 105. — The *Los Angeles* entering the hangar at Lakehurst. This dirigible is 658 ft. long, 90 ft. in diameter, and almost 102 ft. high. The gas bags hold 2 472 000 cu. ft. of gas. The *Los Angeles* weighs 91,000 lb. and can carry a load of 88,190 lb.

to 5000 horse power are used to drive the propellers of huge military dirigibles, some of which measure nearly 700 ft. in length. (See Fig. 106.) The high-school pupil can form a

FIG. 106. — The *R 34* was the first dirigible airship to cross the Atlantic Ocean. The flight from Scotland to Mineola, Long Island (3700 mi.), was made in 108 hr. The actual distance covered, however, was over 7000 mi., an average speed of 67 mi. per hr. The five 12-cylinder engines used develop nearly 1400 H.P. The *R 34*, was 672 ft. long, 90 ft. high, and 79 ft. in diameter. The 18 gas bags inside the duralumin frame had a capacity of 2,000,000 cu. ft. The *R 34* carried 81 petrol tanks, which held 70 gallons each. (*Central News Photo.*)

fairly good idea of the enormous size of such dirigibles, if he stops to consider that the biggest ones are longer than two football fields placed end to end, taller than a five-story school building, and broad enough to accommodate sixteen automobiles abreast.

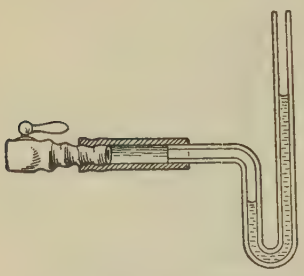


Fig. 107. — To measure gas pressure.

Since air is very compressible, the layers near the surface of the earth are compressed by the weight of the air they sustain, and their density is correspondingly increased. As a balloon rises, it enters an atmosphere that is constantly growing rarer, and the buoyant force of the air is decreasing. A balloon will continue to rise until the weight of the balloon and its contents exactly equals the weight of the air displaced. Water is often carried as ballast, and released if the balloonist wishes to go higher. He may descend by releasing some of the gas. If balloons are filled entirely full before starting, the unbalanced expansive force might tear the gas-bag when the balloon rises into a rarer atmosphere.

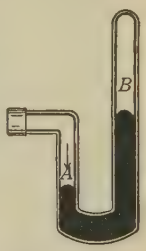


Fig. 108.— Closed manometer.

Fig. 109. — Spring gauge used to measure air pressures.

82. How Gas Pressures Are Measured. We buy gas at a certain price per 1000 cu. ft. Since the density of that gas varies so much with the pressure it sustains, it makes a decided difference whether our gas is measured for us at a low pressure or a high pressure. If we put enough water into a bent tube like that shown in Fig. 107 to stand about 4 in. high in each arm, and attach it to a gas jet, we find that the

water will rise a few inches higher in the open arm when the gas-cock is opened. The difference in height enables us to measure the amount by which the gas pressure exceeds the atmospheric pressure.

Mercury may be used in such a manometer. For high pressures a *closed manometer*, Fig. 108, may be used. A spring gauge, similar to the one shown in Fig. 109, is also used. Most gauges show a reading of zero at normal atmospheric pressure. Hence the actual pressure, or the *absolute* pressure equals the *gauge* pressure plus 14.7 lb. per sq. in. Manometers and gauges may also be used to measure reduced pressures. Engineers speak of a "27-in. vacuum" or a "28-in. vacuum" in referring to reduced pressures. A "28-in. vacuum" means that the pressure is 28 in. less than one atmosphere, which is 30 inches. The gas in a "28-in. vacuum" exerts a pressure of just 2 inches of mercury.

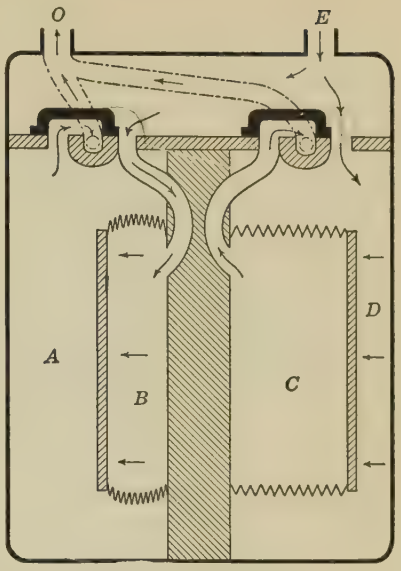


FIG. 110. — A gas meter.

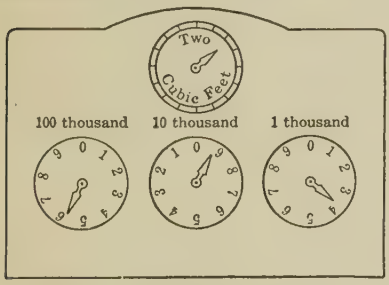


FIG. 111. — Dials of gas meter.

83. The Gas Meter. The gas meter is a metal box divided into four compartments by flexible diaphragms. By a

slide valve these compartments are alternately connected with the city supply and with the pipe to the consumer. While the gas in compartments A and C is being used, the other compartments B and D are being filled. (See Fig. 110.) The movement of the diaphragms not only operates the slide valve but it also controls a clockwork device which records the number of cubic feet of gas that passes through the meter. Fig. 111 shows the dials of a gas meter. An employee of the company reads the meter monthly and determines the amount of gas used each month by subtracting successive readings. The dials in Fig. 111 indicate 59, 300 cu. ft. When the needle stands between two numbers, as on the left-hand dial, the lower number is usually taken as the reading.

SUMMARY

Air has weight. 1 liter of dry air at S.T.P. weighs 1.293 gm. Air also exerts pressure. At sea level the pressure is 14.7 lb. per sq. in.

The rise of liquids in exhausted tubes is caused by air pressure. Torricelli showed that air pressure supports a column of mercury 76 cm. high. Pascal showed that air pressure decreases as the elevation is increased.

A barometer is an instrument used to measure atmospheric pressure. It is used to measure altitudes and in weather forecasting. A rising barometer indicates fair weather. A falling barometer indicates an approaching storm. A steady barometer indicates settled weather.

Unlike liquids, gases placed in a container expand and fill the container. Gases also differ from liquids from the fact that they are easily compressed.

Robert Boyle found that at constant temperature a given volume of dry gas varies inversely as the pressure sustained by it. The density of a gas increases with increased pressure.

Archimedes' principle applies to gases. The buoyant force a gas exerts is equal to the weight of the gas displaced.

Compressed air is used in pneumatic tires, diving bells, air brakes, riveters, and drills.

QUESTIONS

1. Why does a balloon rise? To what height will a balloon rise?

2. In a book that appeared during the war, the following statement was made: "The Germans have discovered a gas which has several times the lifting power of hydrogen." Does the statement appear reasonable? Explain.

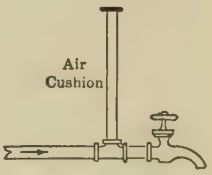


FIG. 112. — Air cushion prevents "pounding."

3. Why do both valves of a pump open upward? Why do they open alternately?

4. Water is often poured into the top of a lift pump to aid in starting it. Explain how it helps. (This operation is called "priming" the pump.)

FIG. 113. — Intermittent siphon.

5. Take a reading of your gas meter on the same day it is read by the company employee. Take a second reading a month later, and calculate your gas bill for the month.

6. A pipe is sometimes fitted to the water pipe near the faucet, as shown in Fig. 112. How does such a pipe, which contains air, keep the water from "pounding" when the water is turned off suddenly?

7. To what height must the siphon shown in Fig. 113 be filled before it begins to flow? To what height must the liquid rise to start the flow a second time?

8. Will a siphon flow if the short arm is more than 34 ft. long? Give a reason for your answer. Will it flow if the long arm is more than 34 ft.?

9. Will a siphon flow in a vacuum? Explain.

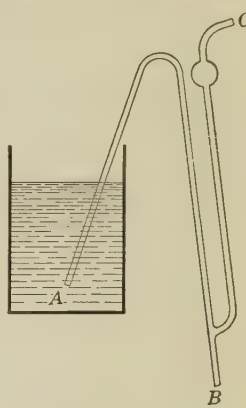


FIG. 114. — Aspirating siphon.

10. The aspirating siphon is used with corrosive liquids. Study Fig. 114, and tell how you would fill such a siphon with liquid to start its action.

11. What is the purpose of the trap in a sink or toilet? (See Fig. 115.) Is it a siphon? If not, try to learn what prevents it from acting as a siphon.

12. Could you siphon water out of the bottom of a boat or canoe? Explain.

13. Why is a small rubber balloon filled with hydrogen apt to burst after it has risen some distance?

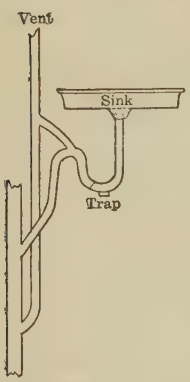


FIG. 115. — Trap for sinks.

14. Explain why a balloon is only partly inflated before a flight is begun.

PROBLEMS

1. If the total weight of a balloon is 1000 Kgm., what must its minimum volume be if it is filled with hydrogen?

2. What volume must the balloon of Prob. 1 have if it is filled with helium?

3. Coal gas is sometimes used for filling balloons. It weighs 0.75 gm. per liter. What is its lifting force?

4. Two balloons have volumes of 1000 cu. m. each. The weight of each one is 150 Kgm. One is filled with hydrogen and the other with helium. How many kilograms can each balloon carry?

5. A lift pump is to be used for pumping oil, sp. wt. 0.85. How high can the oil be pumped by a pump which is efficient enough to pump water 28 ft.?

6. A tire gauge used to test a tire shows a reading of 38 lb. per sq. in. What is the absolute pressure of the air in the tire? Calculate the weight of one liter.

7. What volume must a balloon have to carry a gross load of 10,000 lb. if the balloon is filled with hydrogen?

CHAPTER 4

MOLECULAR PHYSICS

A. MOLECULAR MOTIONS

Vocabulary

Kinetic, moving.
Diffusion, intermingling without regard to weight.
Osmosis, diffusion through membranes.
Surface tension, the contractile property of liquid films.
Adsorption, the condensation of gases on the surfaces of a solid.
Absorb, to suck up, imbibe, or take in.

84. Kinetic Theory of Matter. In § 3, we learned that all matter is made up of exceedingly small particles called molecules. In gases especially, we know that the molecules are by no means relatively near neighbors. In liquids and solids they are crowded more closely, but in all cases there is sufficient space between adjacent molecules to permit the molecules to move freely. The word *kinetic* is derived from the Greek word *kinein*, which means *to move. The kinetic theory of matter assumes that the molecules of all matter are in constant motion.* The rate and nature of such motion depend upon the nature of the substance, its state, and its temperature. There are many evidences that tend to prove the correctness of the kinetic theory.

FIG. 116.—Path of moving particle.

The ultramicroscope shows that very small particles suspended in a liquid are never at rest. They move backward and forward, or dance up and down, in ceaseless motion. These movements are caused by the motion of the liquid molecules, which by their impact drive the particles hither and thither. They are known

as Brownian movements, because they were discovered by Robert Brown, a Scotch botanist. Minute oil drops suspended in air undergo the same zigzag motions as they are driven about by the rapidly moving air molecules. Fig. 116 shows a path taken by a moving particle.

B. MOLECULAR MOTIONS IN GASES

85. Expansion of Gases. If a gas-cock is left open, in a few minutes the odor of gas may be detected in all parts of the room. If we unstopper a small bottle of chlorine gas in a large vessel of air, the yellowish green gas may be seen expanding and mixing with the air in the vessel. The gas molecules move rapidly in all directions until they become thoroughly mixed with the air molecules. Evidently the molecules of these gases are in very rapid motion. A little mustard gas or phosgene will spread quickly to every part of a dugout. Air from the bell-glass, Fig. 77, expands instantly and fills the vacuum formed beneath the rising piston of the air pump. If the molecules of gases were not in constant motion, it would be impossible to produce a vacuum with an air pump. The expansion of gases furnishes one proof of the motion of their molecules.

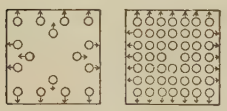


Fig. 117. — Increasing the number of molecules increases pressure.

86. Gases Exert Pressure. Pneumatic tires may burst from the pressure which the air inside exerts on the walls of the tire. This pressure is due to the constant bombardment of the moving molecules. If we pump three atmospheres into the space formerly occupied by one atmosphere, there will be three times as many molecules bombarding the walls of the container, and the pressure will be three times as great. From Fig. 117 we see that tripling the number of molecules in a given space will triple the pressure because there will be three times as many impacts against the walls

as before. The driver of an automobile uses a small pressure gauge to measure the force exerted by the molecules upon each square inch of the inflated tire. By Pascal's law, the pressure is transmitted equally in all directions. If one spot in the tire is especially weak, a "blow-out" may occur. All the devices which utilize compressed air afford examples of gas pressure due to molecular motion. Steam in boilers often exerts a pressure of 200 lb. or more per sq. in. In this case it is also evident that the molecules are widely separated when compared with the diameters of the molecules themselves, for the water formed when steam condenses occupies about $\frac{1}{1600}$ the volume of the original steam. The high temperature increases the velocity of the steam molecules, and the rapidly moving molecules exert great pressure.

87. Diffusion of Gases. Hydrochloric acid is a water solution of a heavy gas, hydrogen chloride; aqua ammonia is a water solution of a light gas, ammonia. When these two gases unite, they form a cloud of fine white particles Suppose we put a couple of drops of hydrochloric acid in a warm bottle, an equal amount of aqua ammonia in a second bottle, cover both with glass plates, and then invert the bottle containing ammonia over the acid bottle, as shown in Fig. 118. After the bottles have stood a few minutes, a vigorous action may be observed when we remove the glass plates. The light ammonia gas moves downward and mixes with the heavy hydrogen chloride, and vice versa. The student will note that the intermingling is apparently contradictory to the laws of weight. Other gases may be used, and they behave in the same manner. For example, carbon dioxide is about 22 times as heavy as hydrogen, but if bottles of these gases are placed mouth to mouth, the hydrogen gas *above* and the carbon dioxide

FIG. 118. — Gases mix by diffusion.

below, some of the molecules of the heavy gas will move upward and mix with the hydrogen and some of the light hydrogen molecules will move downward and mix with the carbon dioxide. If the heavier gas had been placed at the top, we could explain this phenomenon by the laws of weight, but since the gases moved in apparent violation of the laws of weight, it is quite evident that the molecules of gases are in motion. *Such intermingling of gases without regard to weight is called diffusion.*

88. Diffusion through Porous Solids. In the apparatus shown in Fig. 119, an unglazed earthenware cup is closed with a rubber stopper carrying a glass tube which dips into some colored liquid. When a beaker is inverted over the cup and illuminating gas is led into the beaker, air begins to bubble out through the liquid. This experiment shows that gases diffuse through a porous solid. It also shows that the lighter molecules of illuminating gas move faster than the heavier air molecules. If a heavy gas such as carbon dioxide is led into the beaker, then the air molecules flow out through the porous cup faster than the carbon dioxide molecules enter. This reduces the pressure inside the cup and the colored liquid rises in the tube. Osmosis always takes place more rapidly from a less dense to a more dense medium.

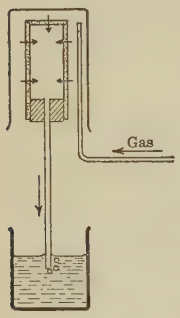


FIG. 119. — Gases diffuse through solids.

The importance of such *diffusion of gases through a plant or animal membrane, which is called osmosis*, can hardly be overestimated. In ordinary breathing, the oxygen of the air passes through the walls of the capillaries in the lungs and enters the blood. It passes through the cell walls in the same manner. Osmosis also occurs in plant tissues. Without osmosis, plant and animal life would cease to exist.

C. MOLECULAR MOTION IN LIQUIDS

89. Evaporation. Everyone knows that water left standing in an uncovered vessel soon disappears by evaporation. It is quite impossible to explain such disappearance of liquids, unless we assume that the molecules of the liquid are in motion. In Fig. 120, we may picture what we believe to be constantly taking place in a liquid. The molecules move in all directions. Only those moving upward can escape into the air. Those that collide with air molecules may rebound into the liquid again. Exhausting the air above the liquid prevents such collisions, and furnishes an explanation for the fact that liquids evaporate more rapidly in a vacuum.

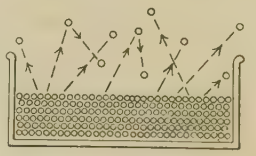


FIG. 120.— Moving molecules escape from surface of liquid.

Other liquids evaporate, some much more rapidly than water, and others very slowly. Evidently the velocities of the different kinds of molecules vary widely.

90. Diffusion of Liquids. Let us pour into a tall cylinder enough concentrated copper sulphate solution to form a layer of blue liquid two or three inches deep. Float a flat cork on the surface of the copper sulphate solution. We can then pour water carefully through a funnel tube on top of the cork so that it will spread out over the surface of the blue liquid, forming two distinct layers, since the water is much less dense than the solution of copper sulphate. (See Fig. 121.)

FIG. 121.— Diffusion of liquids.

After this cylinder stands a few days, the line of demarcation becomes quite irregular. Some of the blue solution moves upward and mixes with the water above, and some of the water molecules move downward into the copper sulphate solution. This experi-

ment shows that diffusion also occurs in liquids. It may require weeks or months before the diffusion is complete, whereas the diffusion between the gases discussed in § 87 was complete in a few minutes. This experiment shows that the molecules of liquids are in motion, but that they move much more slowly than the molecules of gases.

91. Osmosis in Liquids. The apparatus shown in Fig. 122 may be used to show that liquids diffuse through membranes. The diffusion shell *S* and the tube are filled to the mark *A* with a colored sugar solution of 1% or 2% strength. The shell is then immersed in a vessel of water. In a few minutes the liquid begins to rise in the tube, and by the following day it will probably have reached a height of several feet. The light water molecules move much more rapidly than the sugar molecules, and for that reason their penetrating power is greater. In the osmosis of liquids, the diffusion takes place from the less dense to the more dense liquid. The pressure produced by the osmosis of liquids may equal several atmospheres.

FIG. 122.—Osmosis of liquids.

Osmosis of liquids is quite as important as that of gases. The purpose of digestion is to render the food sufficiently fluid to be absorbed by osmosis. Each cell receives its nourishment by osmosis through the cell wall. The mineral matter in the soil dissolves in the water and enters the root hairs of plants by diffusion. Thus plants depend upon osmosis for nourishment.

Oysters are wrinkled when removed from sea-water. They are "fattened" by floating them in fresh water. The osmosis is inward and the body wall is distended by the *osmotic pressure*. To prevent contamination with typhoid bacteria in polluted streams, the Government now decides where oysters may be fattened.

D. MOLECULAR MOTION IN SOLIDS

92. Evaporation. The fact that solids evaporate is not so well known, but a little thought must convince us that solids do evaporate, although in most cases very slowly. A piece of musk will give off enough vapor to be perceived in any part of the room. A lump of camphor gum, or a crystal of iodine, will disappear in a short time by evaporation. Moth balls evaporate completely in time. Snow and ice evaporate quite readily. They disappear when it is too cold for them to melt. It is probable that many other solids evaporate, but so slowly in many cases that it is hardly noticeable. Thus the evaporation of solids furnishes evidence that their molecules are in motion.

93. Diffusion of Solids. If a lead plate and one of gold are left in close contact for a long time, particles of gold may be detected throughout the lead, showing that solids diffuse. The action is so slow that months are needed to produce even a slight diffusion. Other solids show a similar effect if the temperature is increased a few hundred degrees. From the evaporation and diffusion of solids, it is evident that molecular motion exists, even in solids.

E. MOLECULAR FORCES

94. Molecular Forces in Solids. Since there is so much evidence in support of the kinetic theory of matter, the student probably wonders why all substances do not evaporate rapidly and expand indefinitely. Instead we know that many solids have great tensile strength, and that enormous forces are required to pull them apart. In spite of the molecular motion, there seems to be a strong force binding together the molecules of such tenacious solids. *This force of attraction between like molecules is called cohesion.*

Unlike molecules sometimes adhere to one another strongly. Tar sticks to our shoes, glue sticks to wood, and

the dextrine on a postage stamp makes it adhere to an envelope. When we write on the blackboard some of the particles of the crayon adhere to the board. Writing with a "lead" pencil would be impossible, if the molecules of the graphite of which the pencil is made did not adhere to the paper more strongly than they stick together. *The force of attraction between unlike molecules is called adhesion.*

95. Solids, Liquids, and Gases Compared. Generally, the force of cohesion in solids is very great. The moving molecules are so firmly held by this force that they probably oscillate about fixed points, and do not change their relative positions to any marked degree.

In such liquids as tar and molasses, it is evident that the force of cohesion is considerable. In such mobile liquids as water and alcohol, the cohesion is much less, although still measurable. While in liquids the force of attraction between molecules exceeds the effect due to molecular velocities, yet the difference is so small that liquid molecules readily slide over one another; thus the liquid takes the shape of the container.

In gases cohesion is very feeble, and molecular motion so evident that the molecules of gases actually *appear* to repel one another. The force of cohesion is so small that it does not prevent gases from expanding indefinitely.

It seems apparent that the state of matter depends upon the balance between molecular forces and molecular velocities. In a bar of steel cohesion is exceedingly great and molecular velocity seems small. If we warm that piece of steel, its molecules move faster, and its strength is diminished. If we continue to raise its temperature, a point is finally reached where the steel becomes liquid. Its molecules then slide over one another like those of water. At still higher temperatures, steel becomes a vapor, and has the properties of gases.

96. Elasticity. From the preceding section it is easy to see that the tenacity, or tensile strength, of a substance de-

pends upon the cohesion of its molecules. Several other special properties of matter, such as ductility, hardness, and malleability, depend upon cohesion. The elasticity of solids is also dependent upon this force.

It takes a certain amount of force to stretch a rubber band. When the distorting force is removed, the rubber band tends to resume its original length. Such a band is said to be *elastic*, and this type of elasticity which is exemplified by the stretching of a rubber band is called elasticity of *extension* or *traction*. Engineers use the term "stress" in speaking of a force which acts upon a body and tends to distort it. The change produced or the distortion is called "strain." If we squeeze a tennis ball, it becomes distorted, but it tends to recover its original form and size when the stress is removed. This is an example of elasticity of *compression*. The twisting of a coiled spring is an example of elasticity of *torsion*. The elasticity of *flexion* or *flexure* is exemplified by the bending of a strip of steel. In all these cases the body tends to resume its original form when the stress is removed.

97. Measurement of Elasticity. Usually when one speaks of an elastic object, he means one which is easily distorted, such as rubber. Engineers use the term "elasticity" in a different sense. Steel is said to be highly elastic, because it requires a great force to cause its deformation. Steel has a high *elastic constant*.

Suppose we have two wires of different material, but of the same cross-sectional area. If it requires twice as much stress to stretch the first a certain distance as it does to stretch the second the same distance, the former has an elastic constant twice as high as the latter. In this sense steel is the most elastic substance known. Rubber has a very low elastic constant.

98. Perfect Elasticity. If we stretch a coiled spring, it *may* return exactly to its original form after the removal of the

stress. (See Fig. 123.) If it does, it is said to be *perfectly elastic.* If we stretch such a spring too far, it remains premanently distorted. We have exceeded its *elastic limit.* Every material has a certain range of perfect elasticity through which it may be distorted before its elastic limit is reached. For example, it takes a great force to stretch a steel wire, but it cannot be stretched very far without becoming permanently distorted. Its *elastic constant* is high, but its *elastic limit* is low.

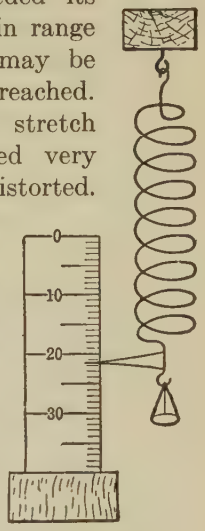


FIG. 123.—Elasticity.

Liquids are perfectly elastic and they have a high elastic constant. Gases have a low elastic constant, as we find if we consider Boyle's law. They are, however perfectly elastic. With both liquids and gases, we are concerned with elasticity of compression *only.* Within the limits of perfect elasticity, the elastic constant of any substance equals $\frac{\text{stress}}{\text{strain}}$. *Stress is the acting force and strain is the change produced.*

99. Rebound. If we throw an elastic object against a hard surface, it rebounds. As a batted ball comes toward him, the shortstop on a baseball team must be able to judge the angle which it will make with the earth, the point at which it will strike the ground, and the angle at which it will rebound. If his judgment is accurate, he can then place his hands in position to catch the ball as it rebounds. In Fig. 124 let the horizontal line represent the ground and O the point at which the ball hits the ground. Suppose we erect a perpendicular OC at O. The line AO shows the path of the

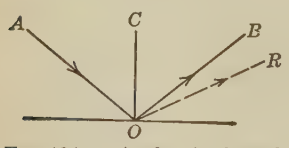


FIG. 124. — Angle of rebound.

ball, and *OB* the line along which it rebounds. If the ball is perfectly elastic and the surface hard, the ball will rebound so that the angle *BOC*, or the angle which the line of rebound makes with the perpendicular, is exactly equal to the angle *AOC*, or the angle that the line along which the ball was batted makes with the perpendicular. *The angle of rebound BOC is equal to the angle of incidence AOC.* In tennis, basketball, billiards, etc., the player is constantly making use of this *law of rebound.*

When a ball that is not perfectly elastic, a dead tennis ball for example, is driven against a hard surface, the angle of rebound, *ROC*, is greater than the angle of incidence. Uneven surfaces and balls that have lost some of their elasticity are responsible for many errors in baseball and tennis.

There is one exception to the law of rebound. A ball spinning on its axis as it moves does not rebound as shown in Fig. 124. A tennis ball that is "cut" to make it rotate is harder to handle, since the player who receives cannot judge the rebound. Of course a ball that is spinning does not travel along a straight line, but along a curve.

FIG. 125. — Tensile strength of wires.

100. Hooke's Law. If we fasten one end of a wire to a beam, as in Fig. 125, and add weights to the hanger attached to the other end, the wire will be gradually stretched as weights are added one by one. Suppose we find that a weight of 100 gm. stretches the wire 1 mm.; then 200 gm. will stretch the wire 2 mm.; 300 gm., 3 mm.; and so on, until the elastic limit is reached. By such methods Hooke found that distortion is proportional to the distorting force, or, in general, *distortions of elastic material are directly proportional to the distorting force, provided the elastic limit is not exceeded.* HOOKE'S LAW may be briefly stated as follows: *Within*

the limits of perfect elasticity, strain is directly proportional to stress. The spring balance is a common example of this law, since the 1 oz. divisions are equidistant.

101. Strength of Materials. It is very important for builders to know the coefficient of elasticity of structural materials. It is just as essential for engineers to know the breaking strength of the materials they use. In physical testing laboratories strong machines are used to measure the strength of materials. Such machines test the tensile strength of cables, ropes, wires, belts, etc. Tests are made of the compression strength of materials used for piers, pillars, posts, and foundations, which must not be crushed by the load they are required to sustain. The propeller shaft of a steamship and the power shaft of an automobile must transmit power without the twisting of the shafts themselves. Torsion machines determine the resistance such shafts offer to a twisting stress. Beams and girders must not bend beyond the limit of perfect elasticity under the load they carry. Several types of beams have been designed to give great strength without undue increase in weight. Fig. 126 shows some of the types that are very much used by structural engineers.

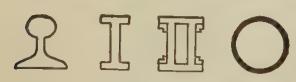


Fig. 126. — T-rail and beams in cross-section.

When designing machines or structures of any kind, engineers always plan to use materials heavy enough to carry several times the load that is likely to be put upon them. This gives a *factor of safety*, for it provides for flaws in the material and for temporary overloading. A bridge which is made of material heavy enough to carry 50 tons is said to have a safety factor of 5, if its load is limited to a capacity of only 10 tons. A cable to be used for an elevator whose gross weight is 3 tons ought to show a breaking strength of at least 9 tons and preferably 15 tons. It should have a safety factor of 3, or better, of 5.

102. Molecular Forces in Liquids. If we stick our finger in a thick molasses and then withdraw it, we are conscious of a certain amount of force needed to pull apart the molecules of the molasses. By use of the following experiment it may be shown that some force is necessary to overcome the cohesion of water molecules. Let us attach a glass plate to one pan of a balance and counterpoise it. Next we shall place a jar of water under the glass plate so that the lower surface of the plate just touches the surface of the water. We may now add several small weights in order to lift the plate. (See Fig. 127.) Since the plate is wet when pulled away, the additional weights must have been used to tear the water molecules apart. The adhesion of the water molecules to the glass is greater than their cohesion for one another; hence water wets glass.

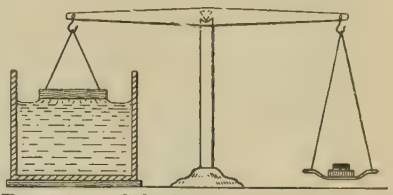


FIG. 127. — Cohesion of water molecules is measurable.

If mercury had been used instead of water, the glass would not have been wet by the mercury, since the cohesion of mercury molecules is greater than their adhesion to glass. For the same reason, mercury does not wet the finger when it is dipped into a bowl of mercury. The force of cohesion varies in different liquids. It is less than in solids, but it is fairly strong in some *viscous* liquids.

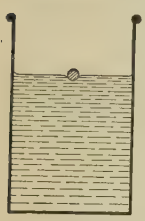


FIG. 128. — Needle floats on water.

103. Surface Tension and Liquid Films. Nearly every one has seen someone float a small sewing needle on the surface of a glass of water. The needle is more than seven times as dense as the water. A careful examination of the water surface shows that the needle floats in a little hollow, as shown in Fig. 128. *The water behaves as if a thin elastic film*

or membrane had been stretched over its surface. This property of liquids is called *surface tension.* The weight of the needle is not great enough to break this liquid film. A wet needle cannot be floated in this manner; hence this experiment is more easily performed if the needle is first covered with a film of oil.

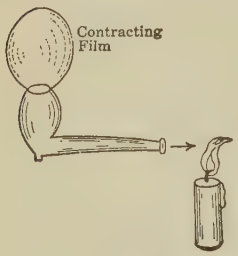


FIG. 129.— Film contracts and expels the air.

Small insects run around over the surface of the water, since their weight is not great enough to break the surface film. All liquids are like water in this respect. In alcohol the film is not so strong as in water. Many oils, however, have a weaker film, but they are much more *viscous.* There is more friction within the liquid itself. Adding soap to the water increases the *viscosity.*

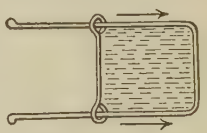


FIG. 130.— Liquid film is contractile.

104. Liquid Films Are Elastic. If we blow a soap bubble and then remove the pipe from the mouth, the bubble slowly contracts, forcing the air out of the pipe-stem. (See Fig. 129.) A film of soap will slide the looped wire along the frame of Fig. 130 as it contracts. When we dip a wire ring containing a loop of thread, Fig. 131 *A*, into a dish of strong soapsuds, a film is formed across the ring. If we break the film inside the loop with a hot wire, the unbroken film outside the loop contracts and pulls the thread into the form of a circle, as in Fig. 131 *B*. These experiments show that *the surface films of*

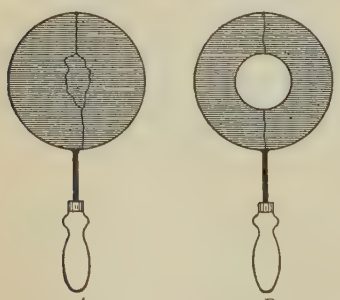


FIG. 131. — *A*. Soap film. *B*. Soap film is contractile.

liquids are elastic. Since this film contracts to make the surface as small as possible, the tendency of liquid films to contract is often called the *surface tension of liquids.*

Reference to Fig. 132 aids in the explanation of surface tension. A molecule at *A* is attracted equally in all directions by the cohesion of the surrounding molecules. A molecule at *B* is attracted laterally and downward, but not in an upward direction. Thus there is exerted upon the surface molecules an unbalanced force tending to pull them toward the interior of the liquid. This unbalanced, contractile force causes the surface to act like an elastic membrane.

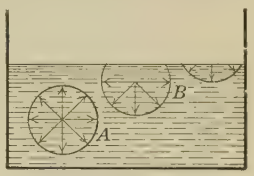


FIG. 132. — Molecule at surface is under uneven tension.

105. Shape of Liquid Surfaces. A careful examination of the surface of the water in a glass container shows that it is not *exactly* level, but it is *slightly concave.* The edge of the surface where it comes into contact with the glass is lifted a little above the general level. (See Fig. 133 *A*.) This crescent-shaped surface of a liquid column is called the meniscus. In reading the height of the water surface in a graduated glass cylinder, we read to the *lower part* of the meniscus, since the actual volume of liquid lifted above this level is small. The reason for the lifting of the water at the edge is explained by the fact that the *adhesion* of the water for the glass is greater than the *cohesion* between the water molecules.

FIG. 133. — *A*. Liquids that wet vessel have concave surface. *B*. Liquids that do not wet vessel have convex surface.

When mercury is used instead of water, the edges of the liquid are depressed and the surface is *slightly convex.* In

this case the cohesion between the mercury molecules is greater than their adhesion for the glass. (See Fig. 133 *B*.) In reading the height of a mercury column, one reads to the *top* of the meniscus.

106. Shape Assumed by a Free Liquid. When we speak of a free liquid, we refer to a liquid that is not subjected to any force or pressure. A little water poured upon the floor is not a free liquid. Under the influence of gravity, the water spreads out in all directions, since its molecules slide over one another readily. Raindrops are nearly spherical; they are common examples of free liquid. If we fill a glass cylinder half full of water, and then float a layer of alcohol on the surface of the water, we can lower a drop of oil into the liquid and practically nullify the force of gravity. The oil is heavier than the alcohol, but lighter than the water. Hence it floats in the mixture. *Its shape is spherical.* (See Fig. 134.)

FIG. 134.—Free liquid assumes spherical shape.

Suppose that one is given a cubic inch of some plastic wax and told to fashion it into such a shape that it will have the smallest surface area that is possible. By geometry, one finds that a sphere has a smaller surface area for a given volume than any other geometrical figure. As the film on the surface of a free liquid contracts, it pulls the liquid into the shape of a sphere, reducing the surface area to a minimum. Mercury spilled on a table breaks up into small drops, since the effect of gravity is small compared to the cohesive force of the molecules of mercury. Larger globules are distinctly flattened.

107. Capillarity. In § 32 the statement was made that liquids in communicating vessels seek the same level. The statement is not rigorously exact, and a correction must be made for communicating tubes of small diameter. Experiment shows that water does not stand at the same level in

communicating tubes of varying diameters, but rises higher in tubes of small diameter, Fig. 135 *A*. When mercury is used, the depression is greater in tubes of small diameter, Fig. 135 *B*. This elevation, or depression, of liquids in *capillary* (hair-like) tubes is known as *capillarity*.

Capillarity really depends upon adhesion and surface tension. The adhesion of water for the glass causes the surface of the water to become concave. Surface tension tends to decrease the surface area, or to flatten it by contraction. The two forces working together lift the liquid above the surrounding level. The height to which the liquid will be lifted depends upon its weight and the strength of the liquid film. In liquids like mercury, cohesion makes the surface convex, and surface tension, by tending to flatten it, produces depression of the liquid in the tube.

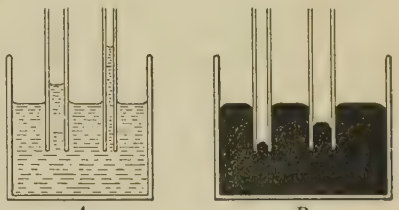


FIG. 135. — *A*. Capillarity of water. *B*. Capillarity of mercury.

108. Laws of Capillarity. Several laws that apply to capillarity have been verified by experiment: (1) *Liquids rise in capillary tubes if they wet them; liquids that do not wet the tubes are depressed.* (2) *The elevation, or depression, is inversely proportional to the diameters of the tubes.* (3) *The amount of elevation or depression decreases as the temperature increases.*

109. Capillary Phenomena in Everyday Life. When one corner of a towel is held in water, other portions of the towel soon become wet. The spaces between the fibers are really small capillaries in which the liquid rises. The use of a towel in drying the hands is an application of capillarity. The absorption of ink by blotting paper, and the rise of oil in a lampwick, are further examples.

Capillarity may play an important part in the conservation of moisture in the soil. Rain water disappears in several ways: (1) Part of it runs off directly; (2) part evaporates; (3) some trickles through the soil and becomes a part of the subterranean drainage system; (4) some of it is absorbed or held by the soil, to be used by the roots of plants. The amount thus retained depends upon the kind of soil and *upon the size of its pores.* In very compact soil the pores are small and capillary action brings the water to the surface, where it is lost by evaporation. Stirring the surface soil makes the pores larger and prevents a considerable portion of this loss. The so-called *dry farming* depends upon this principle. In Kansas, Nebraska, and other states where the rainfall is not much more than fifteen to twenty inches annually, good crops may be grown by making the subsoil compact to prevent subterranean loss, and keeping the surface stirred to prevent loss by capillarity.

110. Solution. Everyone knows that a lump of sugar or a piece of salt put into a glass of water dissolves, or goes into solution. In these cases the water is the *solvent;* the sugar or the salt, the *solute.* It is believed that a substance dissolves if the force of adhesion between its molecules and those of the solvent is greater than the cohesive force binding together its molecules. The molecules of the solute occupy the spaces between the molecules of the solvent. It is probable that molecular motion also plays an important part in the advancement of these molecules through the pores of the solvent.

Several interesting facts concerning solutions should be noted: (1) *A solution is of the same nature throughout;* each unit volume of the solvent contains the same amount of solute. A teaspoonful of sweetened coffee is just as sweet when taken from one part of the cup as from another. (2) *The solute does not separate from the solvent upon standing,* unless the temperature changes or some of the solvent

is lost by evaporation. (3) *Only a definite amount of solute can be dissolved in a given amount of solvent at a certain temperature.* If the solvent holds all the solute it can at that temperature, it is said to be *saturated.* (4) *The solubility of a solid generally increases with a rise of temperature.* Boiling water dissolves salt, sugar, etc., faster than cold water does, and it takes more of the solute to saturate the boiling water. (5) *The solubility of a solid varies with the nature of the solid and with the solvent used.* For example, salt dissolves readily in water, but glass is only slightly soluble. Rosin and shellac are almost insoluble in water, but they dissolve readily in alcohol. Grease is quite insoluble in water, but it dissolves readily in gasoline. On the other hand, many substances that are quite insoluble in alcohol or gasoline dissolve easily in water. Water is one of the best solvents known.

111. Crystallization. When the saturated solution of a solid is cooled or evaporated, some of the solid separates from the solvent in the form of crystals. Crystallization may also occur when a substance changes from the liquid to the solid state. During crystallization the molecules of the solid arrange themselves in regular geometric figures. The shape of the crystal depends upon the nature of the solid and the conditions under which crystallization occurs, Fig. 136. Granulated sugar, rock candy, and snowflakes are familiar examples of this beautiful phenomenon. The diamond differs from the graphite in your "lead" pencil only in the form in which the carbon particles of which it is composed have crystallized.

112. Solution of Liquids. It is possible to dissolve one liquid in another. In such a case, either liquid may be considered the solvent. When two liquids are mutually soluble, they are said to be *miscible.* For example, alcohol and water will mix in all proportions. Oil and water are *immiscible.* When an oily liquid is vigorously shaken with water, finely divided

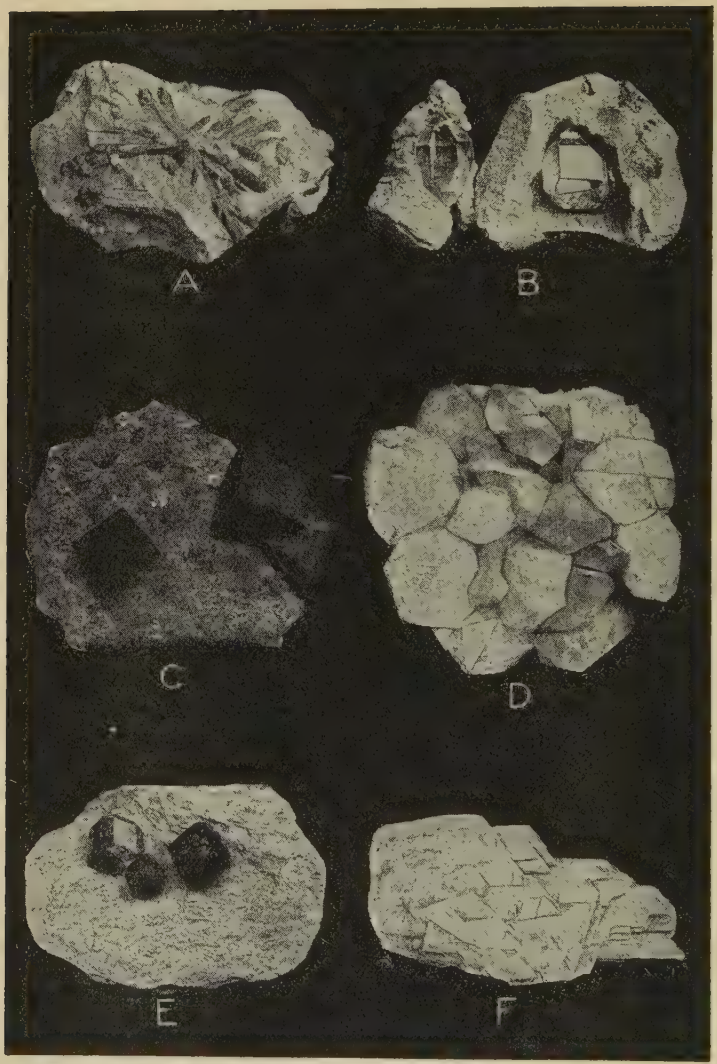


FIG. 136. — Plate of crystals. A. Rubellite. B. Quartz crystal in matrix. C. Galenite, or galena. D. Quartz crystals. E. Garnets on rock. F. Gypsum.

particles of oil remain *temporarily* suspended in the water forming an *emulsion*. Milk is a good example of an emulsion, since the fat globules remain suspended in the milk for some time before the cream separates. In making mayonnaise dressing egg yolks are added to make the emulsion of olive oil permanent.

113. Adsorption of Gases by Solids. Some porous solids, like charcoal, meerschaum, etc., have a great capacity for adsorbing gases. Freshly heated charcoal adsorbs 90 times its own volume of ammonia gas; it will adsorb 35 times its volume of carbon dioxide. The adsorption of gases by solids appears to be due to a condensation of the gas upon the surfaces of the solid; hence porous solids, having large surface areas, naturally have a great capacity for adsorption. Tailors put fuller's earth on a grease spot and then add gasoline. The gasoline dissolves the grease which in the meantime is adsorbed by the fuller's earth. Charcoal is a good deodorizing agent, since it readily adsorbs the gases that give rise to the odors. It was used very extensively in the World War for filling gas masks. It is very efficient in adsorbing poison gases, especially when it is impregnated with certain chemicals. Children in the United States collected cocoanut shells, pits, nuts, etc., to be used for making charcoal for gas masks. It was learned that charcoal made from these substances is about nine times as adsorptive as that made from ordinary soft woods. (See Fig. 137.) The gases that are given off by such foods as fish and onions are readily adsorbed by butter. For this reason butter kept in a refrigerator with onions soon acquires an "onion taste."

114. Absorption of Gases by Liquids. Milk absorbs gases given off by foods quite as readily as does butter. If we heat a little water in a test tube, bubbles of gas soon begin to rise through the water. This gas may be shown to consist of air which was absorbed by the water. Water absorbs carbon dioxide even more readily than it does air, while

FIG. 137. — Official gas mask. Within a week after the Germans released chlorine gas against the Canadians at Ypres, 2,000,000 simple gas masks were distributed to the French and British soldiers. Then projectiles filled with more dangerous gases were used. The simple masks made from veiling filled with "hypo" crystals were replaced by more efficient masks in which charcoal impregnated with chemicals is used to adsorb or destroy the poison gases. (*U. S. Official.*)

ammonia gas is so readily absorbed that it is possible to dissolve nearly 1300 quarts of ammonia gas (S.T.P.) in one quart of ice water.

Heating a liquid decreases its capacity for absorbing gases. In other words, gases are *less soluble* in hot water than they

are in cold water. For this reason ammonia gas is liberated when we heat household ammonia.

An increase of pressure increases the capacity of liquids for absorbing gases. In charging soda fountains, or in bottling carbonated beverages, carbon dioxide gas is forced into the liquid under a pressure of several atmospheres. When the pressure is released, part of the absorbed gas bubbles off and escapes at the surface of the liquid. The effect of pressure upon gas absorption was studied quantitatively by Henry. Hence the statement that *the volume of a gas that can be absorbed by a liquid is directly proportional to the pressure* is known as HENRY'S LAW.

SUMMARY

All matter is made up of very small particles called molecules; these molecules are in constant motion.

Gases expand indefinitely; they exert pressure; they diffuse readily, even through membranes; these facts show that the molecules of gases are in rapid motion.

The diffusion, evaporation, and osmosis of liquids are all evidences that their molecules are in motion. The diffusion and evaporation of solids furnish evidence of molecular motion.

Cohesion is the force of attraction between like molecules; adhesion is the force of attraction between unlike molecules.

When an object rebounds, the angle of rebound is equal to the angle of incidence.

Hooke found that elastic deformations are directly proportional to the distorting force, within the limits of perfect elasticity.

Liquids behave as if a thin elastic film were stretched over their surfaces. This film causes free liquids to assume a spherical shape.

Liquids that wet the tube are elevated by capillary action; those that do not wet the tube are depressed; the amount in either case is inversely proportional to the diameter of the tube.

The solubility of solids usually increases as the temperature increases.

The solubility of gases decreases with an increase in temperature.

An increase in pressure increases the solubility of gases in liquids.

QUESTIONS

1. Why is osmosis of gases and liquids so important?

2. Why does not the carbon dioxide of the air collect near the floor of a room?

3. Why does putting salt on a garden snail or slug cause it to become wrinkled?

4. If a non-corrosive liquid is to be introduced into the eye, why should it have the same density as the fluids inside the cell walls?

5. Explain the action of a towel in drying the hands.

6. Why is a paper that is to be used with ink covered with sizing?

7. When a glass rod is cut off its edges are very sharp. Why do they become rounded when they are held in the flame until the glass is softened?

8. Shot are made by pouring molten lead on sieves supported at a considerable height, from which drops of molten lead fall into a vessel of water. Why are they rounded?

9. A blacksmith welds two pieces of iron together by heating the ends, lapping them, and then pounding them on an anvil. Explain the principle involved.

10. Chemists hold a glass rod against the side of a beaker from which a liquid is being poured. What is its function?

11. Why is a pen to be used for writing with ink split at the point?

12. Is the air inside a soap bubble denser or rarer than the air outside? Explain.

13. Fish die in an aquarium unless the water is frequently renewed. Explain.

14. Why does effervescence occur when soda water is drawn from a soda fountain?

15. Water drawn from the hot water tap quite often appears milky. Explain.

16. What principle of physics does a dentist use when he taps successive layers of gold foil into the cavity of a tooth?

17. What precautions should be taken in storing foods in a refrigerator?

PROBLEMS

1. If the 10-gm. divisions on a spring balance are 2 mm. apart, how far will the spring be stretched by a load of 250 gm.?

2. Given a pound weight, a coiled spring, a metal frame, and a ruler; how would you proceed to make a spring balance to weigh at least 25 lb.?

3. A wire 1 mm. in diameter is stretched 0.1 mm. by a certain weight. How far will a wire 2 mm. in diameter be stretched by the same weight, if it is of the same material and of equal length?

4. Two wires have the same diameter. One of them is 1 ft. long, and it takes a force of 10 lb. to break this wire. How much force will it take to break a piece of the same wire two feet long?

5. If a wire 1 mm. in diameter can support a weight of 25 lb., what diameter must a wire of the same material have to support a weight of 100 lb.?

6. One liter of ice-cold water can absorb 1.7 gm. of carbon dioxide under a pressure of one atmosphere. How many gm. of carbon dioxide can be absorbed at a pressure of five atmospheres?

7. The cross-sectional area of a wire is 0.0002 sq in. If it takes 60 lb. to break this wire, what is its tensile strength?

CHAPTER 5

FORCE

A. GRAVITATION AND WEIGHT

Vocabulary

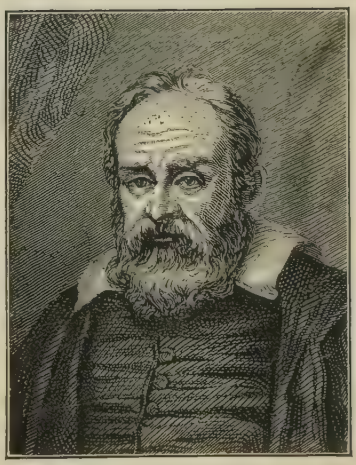
Resultant, a single force that can be substituted for two or more forces without altering the effect.
Equilibrant, a single force that prevents motion.
Center of gravity, that point in a body at which all its weight seems to be concentrated.

115. Force has already been defined as a "push" or a "pull"; it is frequently defined as *muscular exertion* or *its equivalent.* If we pull upon a locomotive, we may move it or we may merely *tend* to move it. In either case we are exerting force. If we push backward against a moving truck, we may stop it or we may tend to stop it. In either case we are using force. Some forces are small and others are stupendous. Forces produce or prevent motion, or they have a tendency to do so. Man sometimes uses the force of the winds, tides, and waves for his own purposes. Sometimes he tries to counteract the destructive force of these agents. Fig. 138 shows one of the "tanks," or land battleships, that played so important a part in the battles of the World War. The large ones were capable of exerting sufficient force to break down barbed wire entanglements and to uproot trees.

116. Force of Gravitation. Probably the most familiar force in nature is that known as *gravitation.* Everyone knows that the earth exerts an attractive force that tends to pull all objects toward it. The child has some experience with the force of gravitation before he learns to walk. We say that objects fall to the earth because they are attracted by gravity.

Sir Isaac Newton (1642–1727) was a famous English philosopher. He stated the law of gravitation and the laws of motion. He discovered the composition of white light, and explained the color fringe of films. In his explanation of the reflection, refraction, and diffraction of light he used as a basis the corpuscular theory. In mathematics he laid the foundation for the calculus.

Galilei Galileo (1564–1642) was an Italian physicist. At the age of eighteen he observed that the oscillations of a swinging chandelier were regular, and invented the pendulum as a time-keeper. From the leaning tower at Pisa he dropped objects of different density and noticed that all struck the earth at practically the same time. Galileo invented the refracting telescope and the thermometer. He showed that the path of a projectile is a parabola.



Sir Isaac Newton called attention to the fact that gravitation is *universal*, and that bodies have a *mutual* attraction. Not only does the earth attract an apple, but the apple has an attraction for the earth. This force of mutual attraction depends upon two things; the masses of the bodies and the

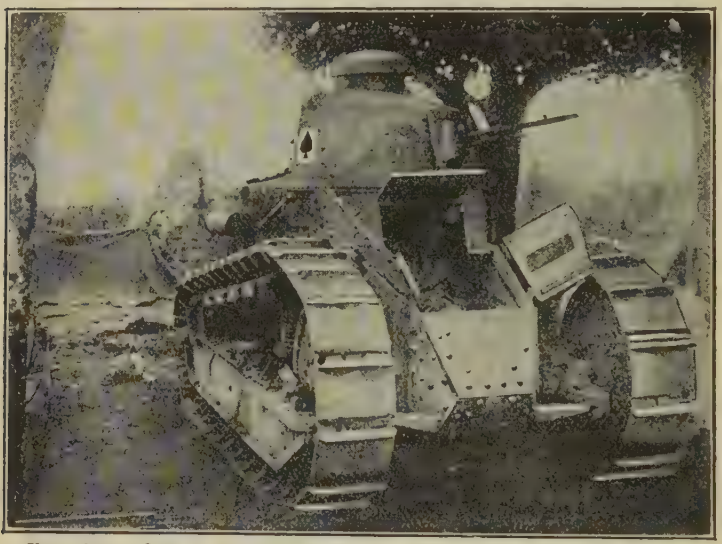


Fig. 138. — One of the small tanks used during the World War. The caterpillar tractor enables the tank to travel over soft or uneven ground. These "whippet tanks" carried machine guns. They could travel as fast as infantry. The larger tanks, Fig. 487, exerted force enough to plow through barbed wire entanglements, uproot small trees, or overthrow small buildings.

distance between their centers. It takes twice as much force to lift two bricks as it does one, because we must overcome the earth's attraction for twice as much mass. If the mass of the earth were doubled, it would attract one brick with twice as much force as it does at present. The force of attraction between two bodies decreases as the square of the distance between their centers increases. The LAW OF GRAVITATION as formulated by NEWTON, is stated as follows: *Every*

body in the universe attracts every other body with a force that is directly proportional to the product of their masses, and inversely proportional to the square of the distance between their centers. An object at the surface of the earth is about 4000 miles from its center. If an object were taken to a height of 1000 miles, it would then be 5000 miles from the earth's center. The earth's attraction for it would be only $\frac{16}{25}$ as great. $(4000)^2 \div (5000)^2 = \frac{16}{25}$.

117. Weight. *The weight of a body is really a measure of the earth's attraction for that body.* When we say that a man weighs 200 lb., we mean that the measure of the earth's attraction for that man is 200 lb., or that the earth pulls that man toward itself with a force of 200 lb. Since all parts of the earth's surface are not equidistant from its center, we would expect the weight of an object to vary in different localities. An object at the top of a high mountain weighs slightly less than it does at the base. Since the earth is a flattened sphere, the poles are nearer the center than the equator; for that reason objects weigh slightly more at the poles than they do at the equator.

The mass of the sun is so much greater than that of the earth that an object which weighs 100 lb. here would weigh about 2700 lb. at the surface of the sun. On the moon, however, the force of gravity is so much smaller that we would weigh only about $\frac{1}{6}$ as much as we do on the earth. An athlete on the moon could easily jump 30 or more feet high; on the sun he would be unable to lift his foot.

118. How Force is Measured. One of the most common methods of measuring forces is by the use of the spring balance. We utilize Hooke's law. The pull of the earth for one gram of mass suspended from the hook of the balance will stretch the spring a certain distance. The earth's pull upon a 2-gm. mass stretches the spring twice as far, and so on. The graduations are marked upon the face of the balance, which is independent of the spring. A pointer attached

to the spring indicates the reading. (See Fig. 139.) In the use of the beam balance for measuring forces, the pull exerted upon one end of the beam is counterpoised by weights of known magnitude upon the other end. (See Fig. 127.)

Fig. 139.—Spring balance.

119. Units of Force. To measure forces, or to compare them, some definite units must be used. In all our work, we have used the *gram of force* and the *pound of force*. They are called the *gravitational units*, since they are based upon the earth's attraction. For example, a gram of force is the pull which the earth exerts upon one gram of mass, and the pound of force is the pull which the earth exerts upon one pound of mass. But the earth's pull upon one gram of mass is greater at the poles than it is at the equator; it is more in a valley than upon a mountain top. For the same reason that weight, or the measure of the earth's attraction, varies, these units also vary. At the latitude of New York, *a gram of force acting continuously for one second upon a gram of mass imparts to it a velocity of approximately 980 cm. per second.* At the equator this velocity is only about 978 cm. per second, but at the North Pole it is about 983 cm. per second. *A pound of force acting for one second upon a mass of one pound imparts to it a velocity of 32.16 ft. per second.*

The student of elementary physics nearly always uses the gravitational units, but engineers must have units of measurement that are independent of the varying force of gravity. The *absolute units* of force are based upon mass and not upon weight. They are also useful in defining other units used in heat and electricity.

In the Metric system the *dyne* is the *absolute* unit of force. *One dyne acting for one second upon one gram of mass imparts*

to it a velocity of one cm. per second. Therefore, the dyne is approximately equal to $\frac{1}{980}$ of a gram of force; or, 980 dynes equal one gram of force at the latitude of New York. In the English system the *poundal* is used as the *absolute* unit of force. *One poundal acting for one second upon one pound of mass imparts to it a velocity of one foot per second.* At New York, one pound of force equals 32.16 poundals.

B. COMPOSITION OF FORCES.

120. How to Represent Forces. Since a force has both magnitude and direction, we may use a straight line to represent a force. The point at which the force is applied must also be considered. Suppose, for example, we wish to represent a force of 10 lb. acting in an easterly direction upon the point P. We may use a straight line ten units long, drawn in an easterly direction from the point P. (See Fig. 140.) Any *convenient* unit may be selected, but it is necessary to use the same unit if several forces are represented on the same diagram. To illustrate, we may let $\frac{1}{4}$ in. represent 1 lb., or 1 mm. represent 1 lb., or any other scale we wish. The choice of the unit to be used will depend upon the amount of space available for the diagram.

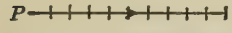


FIG. 140.— Graphic representation of a force.

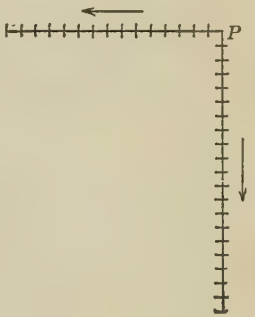


FIG. 141. — Forces acting at an angle.

In Fig. 141, we have two forces represented; one force of 15 gm. acts in a westerly direction upon the point P; the other, a force of 20 gm., acts in a southerly direction upon the same point.

121. Resultant. Quite often two or more forces act simultaneously upon the same point. Sometimes it is desirable to find the point of application, magnitude, and direction

of a *single* force that could produce the same effect as all the forces acting conjointly. *The resultant of two or more forces is that single force which could produce the same effect as the two or more forces acting together.*

The resultant of two or more forces is really a *substitute* for those forces. When the football coach sends a substitute into the game, he removes one player from the field. If we use the resultant or substitute force, we assume that it takes the place of two or more forces. After we have found their resultant, the separate forces need no longer be considered. Unlike the football substitute, who does not always produce the same effect as the man displaced, the resultant force must produce *exactly the same effect* as *all* the forces for which it is substituted.

122. Resultant of Forces Acting in a Straight Line. If we have one boy pulling on a rope with a force of 40 lb., and another boy joins him and pulls in the same direction with a force of 60 lb., the resultant in this case is equal to the *sum of the two forces.* If the boys stopped pulling, one man taking their place could produce the same effect by pulling in the same direction with a force of 100 lb.

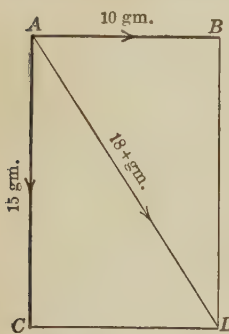


FIG. 142.— Parallelogram of forces.

If one boy pulls in one direction with a force of 40 lb., and another boy pulls in the opposite direction with a force of 60 lb., then the resultant is the *difference between the two forces.* In this case a force of 20 lb. pulling in the direction of the *greater* force would produce the same effect.

123. Resultant of Forces Acting at Right Angles. Suppose one force of 10 gm. acts in an easterly direction upon an object at point *A*, Fig. 142, and another force of 15 gm. acts in a southerly direction upon the same point. Let us first plot

the two forces. It is obvious that the first force acting alone tends to move the object along AB to B. The second force acting alone tends to move the object along AC to C. If the two forces acted *successively* upon the object it would arrive at point D; if they act *simultaneously*, it would also arrive at point D, but its line of motion would be along the diagonal of the parallelogram of which the two forces are sides. *The resultant of two forces acting at an angle upon a given point is equal to the diagonal of a parallelogram of which the two forces are sides.* Students of geometry know that the sum of the squares of the two sides of a right triangle equals the square of the hypotenuse. If we extract the square root of the sum of the squares of the two sides of the parallelogram, we can calculate the resultant. In the above example, $\sqrt{(10)^2+(15)^2}=18+\text{gm.}$

124. Resultant of Forces Acting at Any Angle. It more often happens that the angle between two forces acting upon the same point is not a right angle. In Fig. 143, we have represented forces of 10 gm. and 15 gm. respectively, acting upon the point A. In this case the angle between the two forces is only 50°. Unless the student knows trigonometry, he cannot *calculate* the resultant of these two forces acting at this angle. To find the approximate value of the resultant, we draw a parallelogram, using the two forces AB and AC as sides. We must make the angle between them 50°. From the point A we draw a diagonal and measure it carefully. From the length of the diagonal, we find the equivalent of the resultant force in grams.

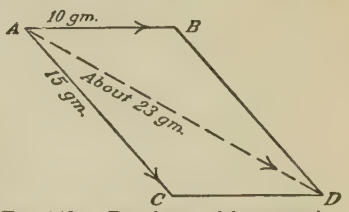


FIG. 143.— Resultant of forces acting at an acute angle.

We find that the resultant is decidedly different if we use the same two forces, but make the angle between them 140°. The parallelogram is constructed in the same manner, using

the forces as sides, and making the angle between them 140°. (See Fig. 144.) Of course the diagonal must be drawn from A. The resultant could never produce the same effect as the two forces acting at A if it were applied at B. The diagonal is measured and its value determined as before.

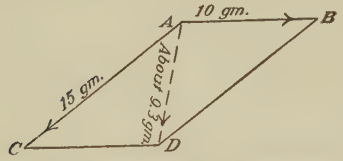


Fig. 144.— Resultant of forces acting at an obtuse angle.

Sometimes three or more forces act at different angles upon the same point. It is possible to find their resultant by finding first the resultant of two of them, using them as sides of a parallelogram, and finding the diagonal. Then we can construct another parallelogram, using as sides the third force and the diagonal of the first parallelogram. The diagonal of the second parallelogram is the resultant of the three concurrent forces.

125. Equilibrant. Sometimes it is desirable to find the magnitude, direction, and point of application of a force which could be applied to produce *equilibrium*, or *to prevent motion*. A boy pulls on a wagon with a force of 40 lb. A second boy pulls on the wagon with a force of 40 lb. in exactly the opposite direction. He prevents motion, or produces equilibrium. The force he uses is called the *equilibrant*.

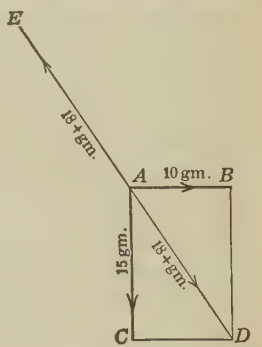


Fig. 145.— Equilibrant prevents motion.

It is quite as easy to find the equilibrant of two or more forces acting upon a point. We must first find their resultant and then apply the equilibrant in an opposite direction. In Fig. 142 we found that a single force, 18 gm., could be substituted for the two forces AB and AC. By removing the two forces, and leaving their resultant AD, we find that the

equilibrant force represented by AE must be applied at the same point A, its direction must be directly opposite to that of the resultant, and its magnitude must be equal to the magnitude of the resultant. (See Fig. 145.) Hence we conclude that *the equilibrant of two or more forces is always equal and opposite to their resultant.*

C. RESOLUTION OF FORCES

126. Resolution of Forces. We have just learned how to find a single force that could produce the same effect as two *component* forces. When the forces acted at an angle, our problem became one of a simple construction in geometry. Given the two sides and the included angle of a parallelogram, to construct the parallelogram and draw its diagonal.

Now if we have given the resultant of two forces acting at an angle, one of the forces, and the angle included between that force and the resultant, we should be able to find the value of the other force. Our problem in this example of *resolution* of forces is the converse of that in *composition* of forces. We have given the diagonal of a parallelogram, one of the sides, and the angle between that side and the diagonal, to construct the parallelogram and find the other side.

PROBLEM. Two forces act upon the point A; one force of 8 gm. acts in a southerly direction; an unknown force acting at an angle with the 8-gm. force produces the same effect as a single force of 10 gm., acting in a direction 37° East of South. Find the magnitude and direction of the unknown force.

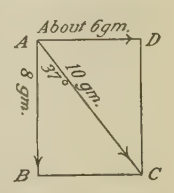


FIG. 146.—Component force is 6 gm.

Solution. Construct a parallelogram, using for one side the 8-gm. force, AB, acting southerly. (See Fig. 146.) Using a protractor, measure off an angle of 37°, East of South, and draw a line AC to represent the resultant force, 10 gm. Use this resultant force as the diagonal of a parallelogram and construct the parallelogram. The side AD of the parallelogram is the unknown force.

127. Resolution of Force of Gravity. *Inclined Plane.* It quite often happens that a force acts upon an object in a direction in which the object is not free to move. Such a force may be resolved into two components. An object resting upon an inclined plane is acted upon by gravity with a force equal to its weight. (See Fig. 147.) The plane prevents the motion of the object in the direction OW, but this resultant force OW may be resolved into two components. One component OD acts perpendicular to the surface of the plane, and tends to break the plane. The other force, OR, acts parallel to the plane, tending to pull the object down the plane.

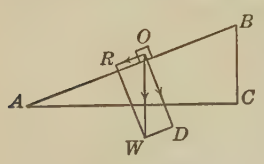


FIG. 147.— Resolution of a force into its components.

Upon the diagonal OW, we may construct the parallelogram $ORWD$, and find the relative values of the sides OR and OD by plotting to scale. In this especial case, we can calculate these values if the height and length of the plane are known. The triangles ABC and WOR are similar. (The sides are mutually parallel and perpendicular.) Hence, $OR : OW = BC : AB$. But OR represents the force tending to pull the object down the plane; OW, the weight of the object; BC, the height of the plane; and AB, the length of the plane. Hence, the force bears the same relation to the weight that the height of the plane does to its length. Or,

$$F : W = h : l.$$

In the same manner it may be shown that the force tending to break the plane bears the same ratio to its weight that the base of the plane does to its length.

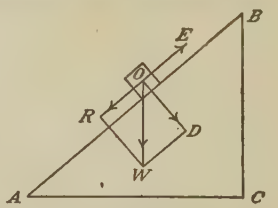


FIG. 148.—OR is greater when plane is steeper.

Making the plane steeper increases the force OR in proportion to the weight and decreases the force OD. (See Fig. 148.) The force OE, which is equal

and opposite to OR, represents the effort needed to keep the object from sliding down the plane. The steeper the plane, the greater this force becomes.

128. Other Applications of Resolution of Forces. When one pushes a lawn mower, he wishes the mower to move along the surface of the ground, but he pushes at an angle to the ground because it is more convenient. The force that he applies, Fig. 149, is resolved into two components.

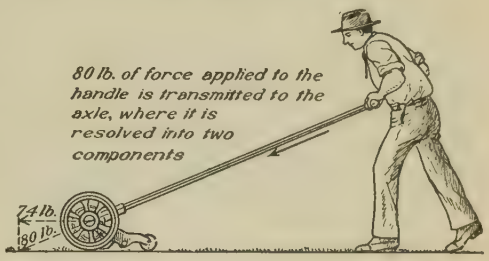


FIG. 149. — The force applied to the handle is resolved into two components.

One component pushes the mower forward parallel with the lawn; the other acts perpendicularly and it tends to push the mower into the ground. Suppose one pushes with a force of 80 lb. at the angle shown in the figure. By constructing a parallelogram to scale, we find that the horizontal component is about 74 lb.; the vertical component, which tends to push the mower into the ground is approximately 31 lb.

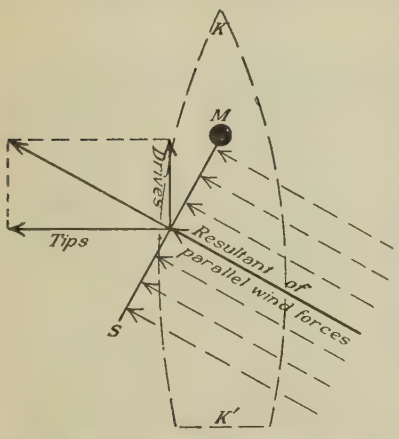


FIG. 150. — Wind acts against sails.

When a boy pulls a loaded sled, the force which he exerts is resolved into two components. The horizontal component draws the sled forward; the vertical component tends to lift the sled vertically.

When a sailboat is moving with the wind, the full force of the wind drives the boat forward. When the boat is moving at an angle with the direction of the wind, part of the force of the wind drives the boat forward, and the other component *tips* the boat. (See Fig. 150.)

In the case of the guy wire on a telephone pole, one component tends to pull the pole into the ground, and the other acts horizontally. When a switch engine on one track pushes a freight car on a parallel track, the thrust force is resolved into two components. One component moves the car along the track, while the other component tends to spread the rails apart. (See Fig. 151.) In the builder's crane or in the steam shovel, the boom must be stiff enough to resist by a thrust force the combined effect of the weight on the rope or chain and the tie force. If the thrust force and the weight are known, the value of the tie force may be found. (See Fig. 152.) In a house or barn, the weight of the roof acts downward and outward upon the walls of the house. By reference to Fig. 153, we can see how the weight of the roof is resolved into the two components. To support a

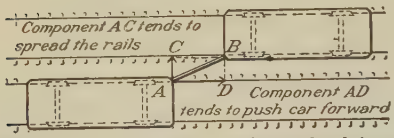


Fig. 151. — The force AB is resolved into two components.

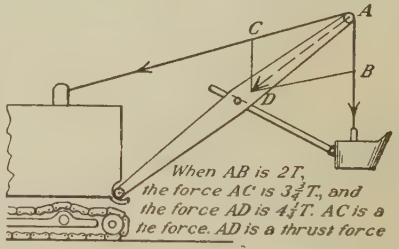


Fig. 152.— How forces are resolved in the steam shovel.

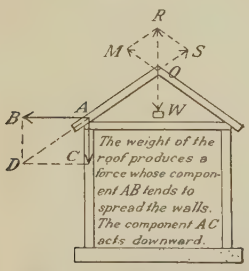
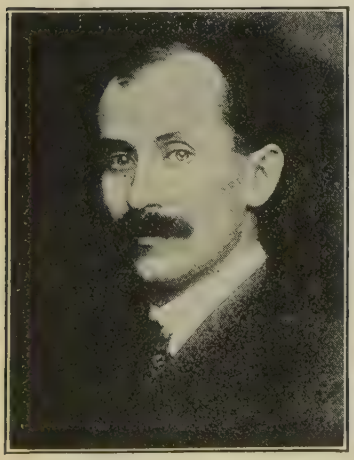


Fig. 153.— Weight of roof presses downward and outward on walls.

weight OW applied at O, the combined upward thrusts OM and OS of the rafters must produce a resultant force equal to OR.

FIG. 154. — First flight with a power-driven airplane at Kitty Hawk, North Carolina, on the 17th of December, 1903. Orville Wright in the plane, and his brother, Wilbur, on the ground. Of four flights made that morning, the longest was 59 seconds, and the distance 852 ft.

129. The Airplane. For centuries men have dreamed of flying. Within the memory of the present generation those dreams have come true. At first men tried the use of gliders.



ORVILLE WRIGHT

WILBUR WRIGHT

The Wright brothers are the inventors of the power-driven airplane.

But in December, 1903, Orville Wright made the first flight in a power-driven airplane at Kitty Hawk, North Carolina. (See Fig. 154.) Now biplanes driven by two powerful motors are used to carry mails. Airplanes maintain regular passenger routes between England and the Continent. Men

Fig. 155. — Colonel Charles Lindbergh and the *Spirit of St. Louis.*

have made altitude flights of about $7\frac{1}{2}$ miles. To range the forests and protect them against fires, and to spray the cotton fields with poisons to kill the boll weevil, airplanes are in common use. Captain Byrd made a flight over the North Pole, and the Atlantic Ocean has been conquered. Colonel Charles Lindbergh flew from New York to Paris, a distance of 3610 miles in $33\frac{1}{2}$ hours. (See Fig. 155.)

The *biplane* has two long, narrow wings, placed one above the other, so that they can be strongly braced. (See Fig. 156.) The wings are slightly curved; they are covered with strong cloth. carefully waterproofed. The wings of many

planes are now being made of light, strong metal. The *monoplane* is faster and more efficient.

Airplanes are driven by light, high-powered gasoline engines. Fig. 372 shows one of the Liberty motors that was developed during the war for use in airplanes. Such a motor weighs about 800 lb. and develops 400 horse power. Fig. 373 shows a Wright whirlwind motor of the type used in the

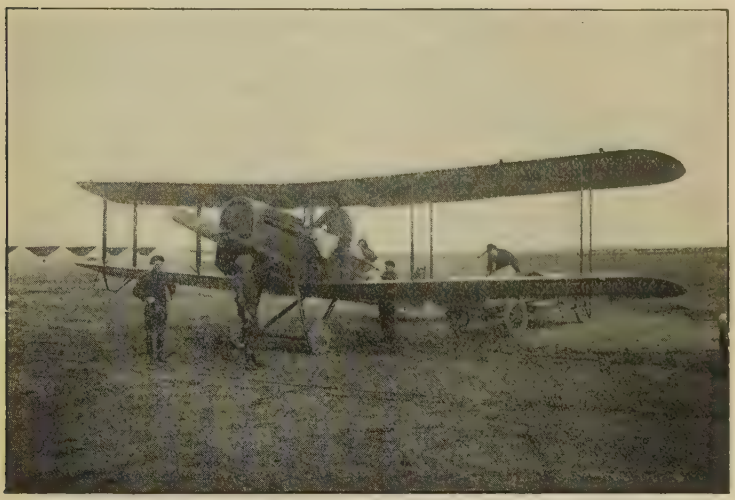


FIG. 156. — Loading mail into one of the U. S. biplanes used for air-mail service.

Spirit of St. Louis. Since airplanes are heavier-than-air, they cannot rise vertically. Hence they must be fitted with wheels to permit them to run along the ground until they acquire sufficient speed to enable them to rise. *Hydroplanes*, or *seaplanes*, are fitted with boat-shaped pontoons to enable them to "take-off" from the water, or to alight upon it.

130. How an Airplane is Supported. Since airplanes are heavier than air, they must be partially supported by the *upward* component of some force. In the monoplane type,

for example, the huge, slightly curved plane is tilted so that the front edge of the plane stands slightly higher than the rear edge. (See Fig. 155.) In normal flight this amounts to only a few degrees, varying from 3 to 6. As the plane is driven forward by the propellers, a breeze is produced which makes the same conditions as if a strong wind were blowing against the plane and the plane were standing still. In Fig. 157 the arrows show the direction of the wind against the plane. Thus the wind exerts a pressure, *CS*, acting nearly at right angles to the plane. This wind force is resolved into two components, one acting vertically, and represented by *CF;* the other component, *CD*, opposes the action of the propeller. This upward component is called the *lift*, and the other component the *drift*. To keep the plane in equilibrium, the *lift* force must equal the weight of the plane, and the *drift* force must balance the forward drive of the propellers.

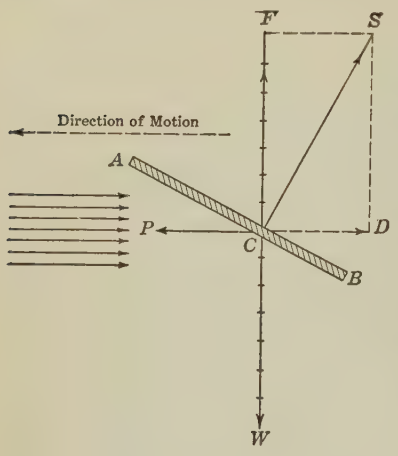


Fig. 157. — Wind force is resolved into two components.

There is another factor which plays an important part in supporting an airplane. As the plane moves forward, the air slides along the surfaces of the plane. But it moves much more rapidly over the upper surface of the plane. Just as the wind blowing across the top of a chimney drags air molecules along with it and reduces the pressure of the air

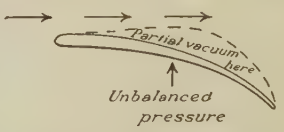


Fig. 158. — The unbalanced pressure helps to support the plane.

in the chimney, so the rapidly moving air reduces the air pressure *above* the plane. Since the air pressure against the lower surface of the plane is greater than that above, the difference in these pressures helps support the plane. This is really an application of a principle stated by Bernouilli. *The high velocity of the fluid moving past the upper surface produces low pressure against that surface, and vice versa.* (See Fig. 158.)

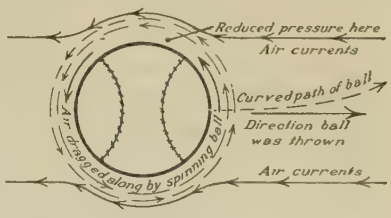


FIG. 159.— Why the baseball curves.

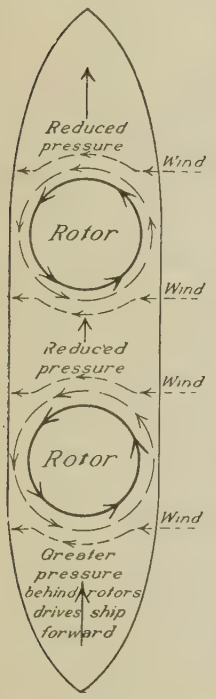


FIG. 160. — The rotor ship.

131. Other Applications of the Bernouilli Effect. *a. Baseball curves.* A baseball which is not spinning may travel in a straight line. But every boy knows that a spinning ball will move along a curved path. If we refer to Fig. 159, we find that the explanation is quite simple. The ball, spinning in a counter-clockwise direction, drags the adjacent air around with it, as represented by the dotted circles. At the top of the ball this air is *moving with* the air current set up by the forward motion of the ball, and at the bottom it is *moving against* these currents. The air at the top moves faster and the pressure there is reduced. Thus the ball will move along the path shown by the dotted curve.

(*b*) *The rotor ship.* The ship designed by Flettner is also an example of the

BERNOUILLI PRINCIPLE. The two rotors, Fig. 160, are turned by machinery. The adjacent air is dragged around with these rotors. The wind blows at right angles to the direction of the ship's motion. On the side of the rotor toward the stern of the vessel, the revolving air currents meet the wind drift and the velocity is reduced. On the bow side of the rotor both currents move in the same direction, and the velocity is increased. But high velocity produces low pressure on the bow side of the rotor and low velocity produces high pressure on the stern side. Hence the difference in the air pressures on the opposite sides of the rotor pushes the boat forward.

QUESTIONS

1. If a hole were bored through the earth and a ball dropped into it, where do you think it would come to rest? Explain.

2. A professor at Oxford University went before his class, threw a ball into the air, and remarked: "Behold, gentlemen! I throw a ball into the air; the earth rises to meet it, and the stars in heaven bow down to greet it." Explain what he meant.

3. Would a gram of force at the sun be greater than a gram of force at the earth's surface?

4. Is a dyne of force greater at the sun's surface than it is at the surface of the earth? Give a reason for your answer.

5. Why would you lower the handle of a lawn mower in pushing it through tall grass? Use a diagram to clarify your explanation.

6. Does a man weigh more at the North Pole or at the equator? Does he weigh more on top of a mountain or at its base?

7. A spring balance is graduated to read pounds at New York. If this balance were used to weigh meat at the North Pole, would you get more meat or less in a 5-lb. roast? Suppose a platform balance were used, would you get more meat at New York or at the North Pole?

8. A hammock is 8 ft. long. Is it more apt to break if the ends are attached to posts 5 ft. apart or 7 ft. apart? Use a diagram to explain.

9. Can a boy support the weight of his body more easily if he

grasps the bar of a trapeze with his hands 1 ft. apart, or if his hands are 2 ft. apart? Explain. To be sure you are right, try the experiment.

PROBLEMS

1. A force of 30 gm. acts in an easterly direction. Upon the same point a force of 25 gm. acts in a southerly direction. Represent graphically, and find the magnitude of the resultant.

2. Find the resultant of two forces acting upon the same point, one of 60 gm. acting easterly and the other of 45 gm. acting northerly.

3. Two forces, 8 and 10 lb. respectively, act upon a point P. Find their resultant: (*a*) when the angle between them is 180°; (*b*) when the angle between them is 120°; (*c*) when the included angle is 90°; (*d*) when it is 60°; (*e*) when it is zero.

4. A force of 50 lb. acts easterly upon the point P. A force of 70 lb. acts southwesterly. Represent graphically. Show the position of the equilibrant, and find approximately the value of the resultant.

5. Find the resultant of two 60-lb. forces, if the included angle between them is 60°.

6. Find the resultant of three forces acting upon the same point. One of 15 lb. acts northerly, one of 20 lb. acts easterly, and one of 25 lb. acts southeasterly.

7. An inclined plane is 13 ft. long and 5 ft. high. A weight of 156 lb. rests on the plane. Find the value of the component acting at right angles to the plane, and the component tending to pull the weight down the plane.

8. A weight of 200 lb. is supported by a rope. If the rope is drawn aside along BC, Fig. 161, by a force of 80 lb., find the tension on the rope AB.

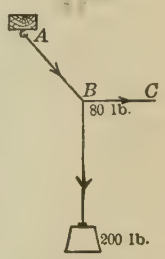


FIG. 161.—Component of force.

9. The resultant of two forces acting on an object is 20 lb. The forces are equal and act at right angles. Find their magnitude.

10. A man pushes with a force of 50 lb. against the handle of a lawn mower. If the handle makes an angle of 30° with the level of the ground, find the component of the 50-lb. force which pushes the mower forward, and also the vertical component.

11. A picture is hung from a hook by means of a wire. The two divisions of the wire make an angle of 90° at the hook, and the tension in each one is 12 lb. Find the weight of the picture.

12. A person who weighs 160 lb. sits in the center of a hammock. The ropes supporting the hammock make angles of 60° with the posts to which they are attached. Find the tension on each rope.

13. A child weighing 90 lb. sits in a swing. Find the tension on the ropes when a man pushes against the swing with a force of 30 lb.

D. PARALLEL FORCES

132. Moment of a Force. Sometimes two forces act on the ends of a bar which is pivoted at some point between the forces. Let Fig. 162 represent a rigid bar AB, upon the ends of which two parallel forces, F and F', are acting. This bar is free to turn about the pivot or fulcrum at C; this point is also called the *center of moments*. The force F tends to pull the bar around in a clockwise direction, and the force F' tends to pull the bar around in a counterclockwise direction. The effectiveness of such a force in producing rotation, or the *moment of the force*, depends upon two things: 1. *The magnitude of the force;* 2. *The length of the arm upon which it acts*, or the distance from the point at which it is applied to the pivot. *The moment of a force is equal to the product of the force times the length of the arm upon which it acts.* For example, if F is a force of 20 lb., and the arm BC upon which it acts is 4 ft., then its moment is 80. If F' is a force of 40 lb., and the arm AC upon which it acts is 2 ft., then its moment is 80.

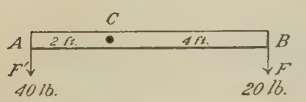


FIG. 162. — Parallel forces.

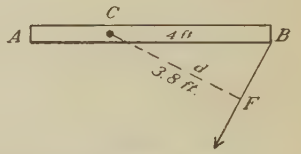


FIG. 163. — Force acts at an angle.

If the force F is not applied perpendicularly to the bar AB, as shown in Fig. 163, the distance from B to C cannot be

used as the length of the arm upon which the force acts. In such a case we use the perpendicular distance d from the center of moments C to the line of direction of the force. The moment in this case is Fd.

133. Parallel Forces. Two horses pulling a loaded wagon furnish an example of parallel forces. If the hole is bored through the doubletrees in the middle, both arms will be of equal length, and each horse must pull with the same force to move the load. If one horse is much stronger than the other, he can be made to pull the major part of the load by boring the hole through the doubletrees, or evener, an inch or two from the center, and hitching the stronger horse to the short end.

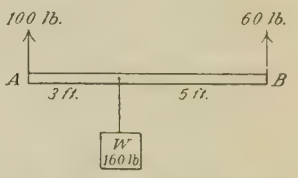


FIG. 164.— How a load is apportioned between parallel forces.

Two boys carry a load on a stick between them. (See Fig. 164.) The stick is 8 ft. long. The load, which weighs 160 lb., is placed 3 ft. from the boy at A, and 5 ft. from the boy at B. Let us inquire what part of the load each boy carries. To find the upward force the boy at A must use, let us consider that the hand of the boy at B acts as a center of moments. A is pulling upward (clockwise) upon an arm 8 ft. long. Let x equal the force he exerts. Then the clockwise moment equals $8x$. But the load W is pulling downward (counter-clockwise) with a force of 160 lb. upon an arm 5 ft. long. Its moment is 5×160, or 800. If the bar is in equilibrium, the two moments are equal. Then $8x = 800$. And x, the force at A, is 100 lb. To find the force needed by the boy at B, we assume that the center of moments is at A. Then the upward force, x, at B acts counter-clockwise upon an arm 8 ft. long. The load, 160 lb., acts clockwise upon a 3 ft. arm. The moments are $8x$ and 480 respectively. Since $8x = 480$, then $x = 60$, the force at B. In these cases the weight of the stick was not considered.

The ends of a bridge pushing down upon the piers or abutments furnish another example of parallel forces. The force acting downward upon each pier is the same as the force needed to lift the end of the bridge at that pier. Suppose the bridge AB is 100 ft. long, and a weight of 10,000 lb. rests on the bridge 30 ft. from A., Fig. 165. Suppose we neglect the weight of the bridge. The clockwise moment at A equals $100x$; the counter-clockwise moment of the weight on the bridge is $70 \times 10{,}000$, or 700,000. Since these moments are equal, $100x = 700{,}000$, and $x = 7000$ lb. The number of pounds supported by pier B is found in a similar manner. Using A as the center of moments, we find that $100x = 30 \times 10{,}000$. Whence $x = 3000$ lb. If the weight of the bridge is distributed uniformly along its length, then each pier will support an additional weight equal to half the weight of the bridge.

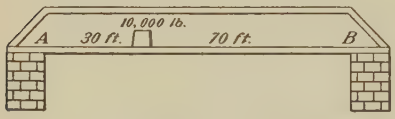


FIG. 165.— Parallel piers support bridge.

134. Resultant and Equilibrant of Parallel Forces. To produce the same effect as two parallel forces acting in the same direction, a single force would need to act in the *same* direction as the forces and to equal their *sum*. A little thought must also convince us that the resultant of parallel forces must be *applied at their center of moments*. If it were applied at any other position, it would produce rotation.

It is also an obvious fact that a third force (equilibrant) used to counteract the effect of two or more parallel forces, must equal the *sum* of all the forces, and it must be *applied at their center of moments*. Of course it must act in an *opposite* direction.

E. CENTER OF GRAVITY AND EQUILIBRIUM

135. Center of Gravity. As a stone lies upon the ground, Fig. 166, the earth attracts every particle of it. All these

downward forces which the earth exerts are parallel. Evidently the resultant of all these parallel forces is equal to their sum, which is the weight of the stone. The point of application of this resultant is called the *center of gravity.* The center of gravity of any object is that point at which *all its weight appears to be concentrated.* If we attach a string to a stone, at a point directly above the center of gravity, and pull upward, the stone can be lifted without any rotation. An object will balance on the point of a knife placed directly beneath its center of gravity. When we try to overturn the stone shown in the figure, the point B becomes the center of moments; A is the clockwise force acting upward, and the *whole weight* of the stone, concentrated at its center of gravity acts counter-clockwise. If we consider AB as the arm upon which the effort acts, and CB as the arm upon which the weight acts, it is easy to understand why it is easier to overturn a stone than it is to lift it.

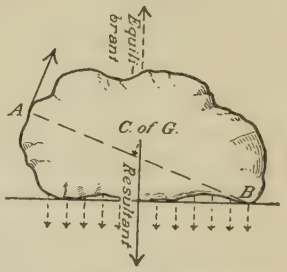


FIG. 166.— All the weight appears to be concentrated at the center of gravity.

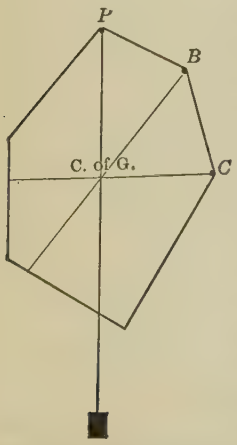


FIG. 167. — Finding center of gravity.

136. Center of Gravity by Experiment. If we suspend a weight by means of a small cord, the line along which it will come to rest will, if produced downward, pass through the center of gravity of the earth. Such a weight and cord form a plumb line. If we wish to find experimentally the center of gravity of an irregular object, such as that shown in Fig. 167, we first

suspend it from the point P in such a manner that it may turn freely about the point of suspension. The object will swing about this point and come to rest with its center of gravity directly below the point of support. Now if we drop a plumb line from the same point of support, the center of gravity of the object will coincide with some point in the plumb line. A line drawn along the plumb line must pass through this point. Next let us suspend the object from the point B, and again draw a line in the direction indicated by the plumb line. For verification, we may repeat the operation, this time suspending the object from the point C. Each of these lines passes through the center of gravity. Therefore the center of gravity of the object lies at the point of intersection of these lines. In his work in mechanics, the student will find it very convenient to consider that *an object behaves as if all its weight were concentrated at its center of gravity.*

137. Equilibrium. A book lying on a table pushes down upon the table with a force equal to its weight. The table must push upward with an equal force if the book remains in equilibrium. In order to keep the book or any other object in equilibrium, there must be no unbalanced force acting upon it. A push from one side must be balanced by an equal push from the opposite side. *An object is said to be in equilibrium when no unbalanced force acts upon it.* In other words, *the resultant of all the forces acting upon it is zero.*

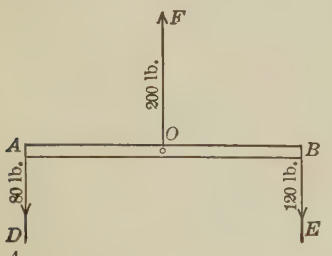


FIG. 168. — Force at F prevents translatory motion.

To secure equilibrium, two kinds of motion must be prevented: *translatory*, or motion along a line; and *rotary*, or motion about a point acting as a pivot. Suppose we have two parallel forces, D and E, of

80 and 120 lb. respectively, acting upon a bar at points A and B, Fig. 168. A force of 200 lb. applied in the opposite direction at O will prevent translatory motion, but it will not prevent rotary motion. Rotary motion may be prevented if the force of 200 lb. is applied at the center of moments, x, Fig. 169. Suppose the bar is 20 ft. long, then the equilibrant must be applied at a point 8 ft. from B, the greater force. The lengths of the arms upon which the two forces act is inversely proportional to the magnitude of the forces.

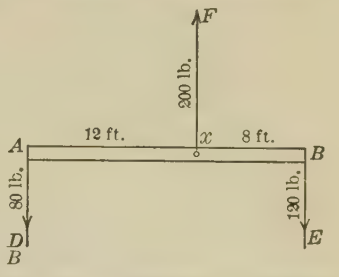


FIG. 169. — Force at x produces equilibrium.

PROBLEM. A bar 30 ft. long is pivoted so that it is free to rotate about the point C, Fig. 170. At A, 6 ft. from C, a force of 400 lb. acts downward; at B, a force of 50 lb. acts downward; at D, 10 ft. from C, there is a downward force of 100 lb.; at E, 4 ft. from B, a force of 80 lb. acts upward; and at F, 2 ft. from A, a force of 250 lb. acts upward. Neglecting the weight of the bar, where must a force of 200 lb. be placed to secure equilibrium, and in what direction must it act?

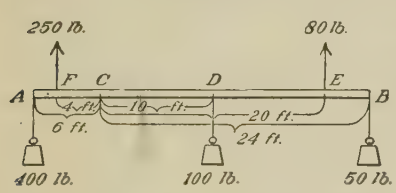


FIG. 170. — The bar is in equilibrium when the algebraic sum of the moments is zero.

Solution. The forces B, D, and F act clockwise; their distances from C (all distances must be measured from the center of moments) are 24, 10, and 4 ft. respectively. The forces A and E act counter-clockwise; their distances from C are 6 and 20 ft. respectively. We solve the problem by finding the difference between the sums of the clockwise and counter-clockwise moments. Then we may let x equal the distance that

a 200 lb. force must be placed from C to produce equilibrium. Its moment, $200x$ must equal the difference.

Clockwise moments	Counter-clockwise moments
$24 \times 50 = 1200$	$6 \times 400 = 2400$
$10 \times 100 = 1000$	$20 \times 80 = 1600$
$4 \times 250 = 1000$	sum $= 4000$
sum $= 3200$	3200
	difference $= 800$

Since $200x = 800$, then $x = 4$ ft., the distance from C the 200-lb. force must be placed. Since the counter-clockwise forces are greater, it must be used as a clockwise force. Hence, it may act downward 4 ft. to the right of C, or upward 4 ft. to the left of C.

Any number of parallel forces are in equilibrium if the sums of the opposite forces are equal, and the sums of all the clockwise moments are equal to the sums of all the counter-clockwise moments.

138. Stable Equilibrium. If an object is in stable equilibrium, it cannot be overturned without first raising its center of gravity. If slightly tipped, it tends to return to its former position. The blocks shown in Figs. 171 and 172 are both in stable equilibrium, but their degree of stability differs. To overturn block (A) about the edge E, the center of gravity C must be raised to the point A. When the center of gravity passes beyond the vertical line AE, so that it falls outside the area included within the base, the block will be overturned and fall to the position shown by the dotted lines. The same block, standing on end, Fig. 172, is also in stable equilibrium, but it is not so hard to overturn it as when it lies flat on its side. In the position shown in Fig. 171, the center of gravity must be

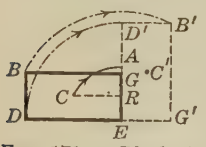


FIG. 171. — Block is very stable.

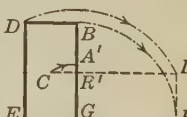


FIG. 172.— Block is stable, but less stable than in Fig. 171.

lifted the vertical distance RA before it can be overturned; in the position shown in Fig. 172 the center of gravity must be lifted from R' to A' before it can be overturned. RA is much greater than $R'A'$; hence the greater stability when the block lies on its side. *The stability of an object may be increased by enlarging the base and by having the center of gravity as low as possible.*

The base of support is represented roughly by the area inclosed by the perimeter drawn around the supporting members. The dotted lines of Fig. 173 inclose the area of the base. With a three-legged stool the base is triangular; with an ordinary chair it is a rectangle.

FIG. 173. — Base of support.

A boat loaded with freight sinks very low in the water; at the same time the center of gravity is lowered, increasing its stability. A load of stone is less apt to be upset than a load of hay, since the center of gravity of a load of stone is lower. In Fig. 174 the loaded wagon on the sloping road will upset when the load is high enough to have its center of gravity at C'. A plumb line let fall from C' falls outside the wheel base. If that part of the load, represented by the dotted line, is removed, the center of gravity is made lower. A plumb line let fall from C falls within the area described by the wheel base, and the load is stable.

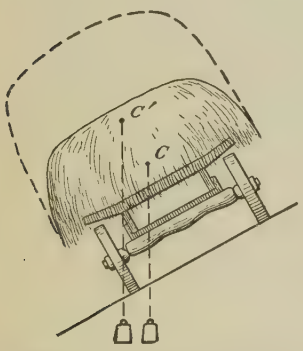


FIG. 174. — Wagon is stable when plumb line falls within area of base.

139. Unstable Equilibrium. An egg standing on its end is in unstable equilibrium. A person walking a tight rope is another example. As soon as the slightest displacement oc-

curs in either case, the center of gravity falls outside a plumb line perpendicular to the point of support; it begins to be lowered at once, and the object falls. In unstable equilibrium the center of gravity is above the point of support.

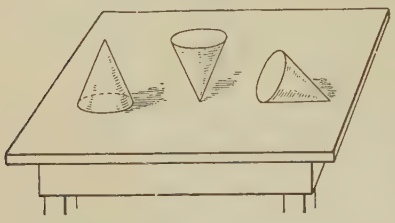


Fig. 175. — Types of equilibrium.

140. Neutral Equilibrium. A ball lying on a table is in neutral equilibrium. A cylinder or a cone lying on its side, and a wheel free to turn upon its axle, are other examples of neutral equilibrium. Such objects come to rest in any position since the center of gravity is neither raised nor lowered when the object is overturned. (See Fig. 175.)

SUMMARY

Force is a "push" or a "pull"; it tends to produce, change, or check motion.

Gravitation is the attraction between masses. The force of attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

The gram of force and the pound of force are gravitational units of force. The dyne and the poundal are absolute units of force.

The resultant of two or more forces is that single force which could produce the same effect as two or more forces acting together. The resultant of forces acting in the same direction is their sum; the resultant of forces acting in opposite directions is their difference.

The resultant of two concurring forces acting at an angle is equal to the diagonal of the parallelogram of which the forces are adjacent sides. The equilibrant is that force which produces equilibrium; it is equal to the resultant and opposite in direction.

A single force may be resolved into two or more components. In such a case the single force is represented by the diagonal of a parallelogram of which the two components are sides.

The center of gravity of a body is that point at which all its weight appears to be concentrated.

An object is in equilibrium when the resultant of all the forces acting upon it is zero. The stability of an object is increased by broadening its base and by lowering its center of gravity.

QUESTIONS

1. In what two ways can a football guard increase his stability?

2. Compare a picture of a modern automobile with that of the early models. What are the advantages of the low, "underslung" models from the standpoint of stability? (See Figs. 176 and 177.)

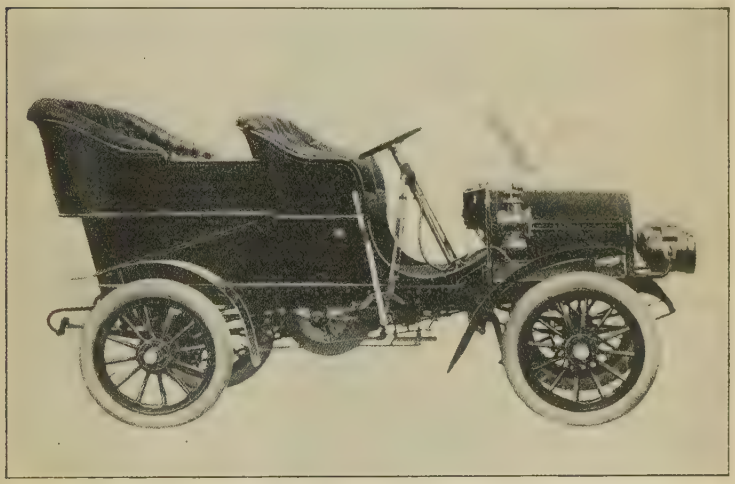


Fig. 176. — Observe the high center of gravity of this 1904 model.

3. Why does the oil-can shown in Fig. 178 right itself when placed on its side?

4. Why does a ball roll down hill?

5. Why does a man lean forward as he climbs a hill?

6. What type of equilibrium is exemplified by a person (a) standing in a canoe? (b) lying in the bottom of a canoe?

7. What is the purpose of ballast on an ocean vessel? Where is it placed?

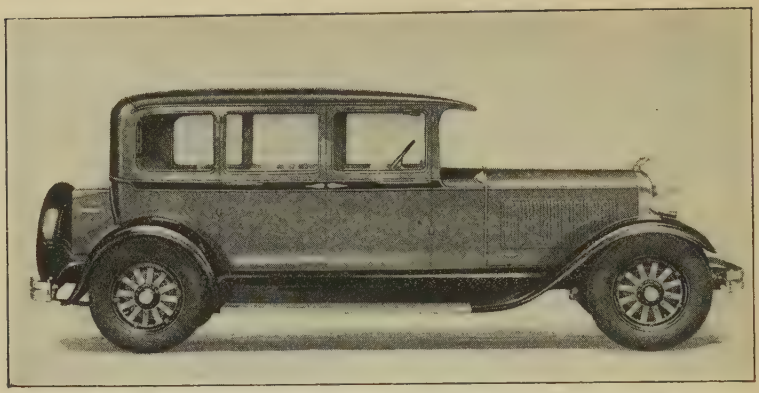


FIG. 177. — The "underslung" chassis of the same make of car twenty-five years later.

8. It is difficult to balance a bowl on the end of a finger if the bowl is upright, but it is easy when the bowl is inverted. Explain.

9. A man has a tall, slender vase. In what two ways can he increase its stability?

10. Why does a tight-rope walker carry a long pole?

11. Explain why the Great Pyramids are so very stable.

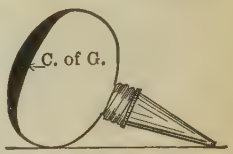


FIG. 178. — Oil-can.

12. A man carries a heavy bag on a stick swung over his shoulder. Explain why the handle of the bag should be kept close to his shoulder.

13. Why does a block of wood $10 \times 6 \times 2$ in. float on one side instead of an edge or an end?

PROBLEMS

1. A steel bar 10 ft. long weighs 300 lb. How much force must a man exert to pick up one end of the bar, if its center of gravity is in the middle? 150

2. A tapering bar 10 ft. long weighs 300 lb. If its center of gravity is 3 ft. from the larger end, how much force must a man use to lift the smaller end? What force must he use to lift the other end? 90 210

3. Two boys carry a load of 140 lb. on a stick 3.5 ft. long. If the load is placed 2 ft. from the smaller boy, how many pounds does each boy carry? 80 lb. 60 lb.

4. A bridge is 200 ft. long. A load of 5 tons rests on the bridge at a point 30 ft. from one end. What load does each pier or abutment sustain, in addition to the weight of the bridge?

5. A bridge 80 ft. long weighs 6 tons. An engine weighing 8 tons crosses the bridge. What is the maximum load sustained by each pier? The minimum load? The load when the engine is 25 ft. from one end?

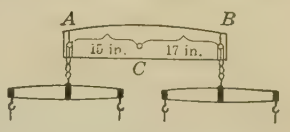


FIG. 179. — Double-trees, or evener (parallel forces).

6. A pair of doubletrees is 32 in. long. If a hole is bored 15 in. from one end, how many pounds must each horse pull, if hitched as shown in Fig. 179 to a load of 480 lb.?

7. A painter's scaffold weighing 200 lb. is suspended by two parallel ropes 12 ft. apart. Find the tension on each rope. A painter weighing 156 lb. stands on the scaffold two feet from one rope. Find the tension on each rope. Find the tension on each rope when another painter weighing 144 lb. steps on the scaffold at a point 3 ft. from the other rope. (The student should always make a diagram in solving problems of this type.)

8. A bar 6 ft. long is pivoted at C, 30 in. from the end A. A downward force of 40 lb. is applied at A; at B, the other end, an upward force of 60 lb. is applied; at D, 10 in. from A, there is an upward force of 100 lb.; at E, 12 in. from B, there is a downward force of 120 lb. Where must a force of 94 lb. be applied to produce equilibrium, and what is its direction?

9. A bar 10 ft. long has its center of gravity 3 ft. from one end. It balances on the edge of a block placed 5 ft. from the smaller end of the bar when a weight of 40 lb. is hung at this end. Find the weight of the bar. (Consider that all its weight is at its center of gravity.)

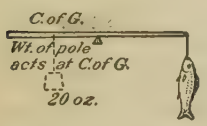


FIG. 180.—Weight of pole at *C. of G.* counterbalances the fish.

10. A man has a fish pole 10 ft. long which weighs 20 oz. He finds by balancing it on the edge of a board that its center of gravity is 30 in. from the larger end. He catches a fish, and then finds that the pole with the fish attached as in Fig. 180 now balances in the middle. Find the weight of the fish.

CHAPTER 6

MOTION

A. TYPES OF MOTION

Vocabulary

Velocity, rate of motion.
Acceleration, rate of change of velocity.
Oscillation, a backward and forward motion, or vibration.
Momentum, the quantity of motion.
Centrifugal, pulling or reacting from the center.
Centripetal, directed or pulled toward the center.

141. Motion. *We may define motion as a change of place or position.* Both motion and rest are relative terms. A person sitting in a railway coach is at rest with respect to the parts of the coach, but he may be in motion with respect to the surrounding landscape. One walking along the decks of a moving steamship is in motion with respect to the parts of the ship and also with respect to the earth's surface. Motion is *rectilinear*, if the object moves along a straight line; if the object moves along a curved line, the motion is *curvilinear*.

142. Velocity *is the rate of motion;* the velocity of an object is the distance it moves in a given unit of time. Velocity may be expressed in miles per hour, feet per second, kilometers per hour, etc. For example, we say that a train has a velocity of 60 mi. per hr. (Fig. 181), that a rifle bullet travels with a velocity of 3000 ft. per sec., or that a man runs with a velocity of 30 ft. per sec. The word "speed" is practically synonymous with "velocity"; the slight difference in meaning is not of importance for secondary school pupils. Motion is *uniform* when the velocity is constant,

or when the distance traversed is the same for each succeeding unit of time. A car that *maintains* a velocity of 30 miles per hr. is an illustration of uniform motion. When the distances traversed in equal periods are unequal, the motion is *variable.*

FIG. 181. — Broadway Limited running 60 miles per hour. This train runs between New York and Chicago (about 950 miles) in 20 hours.

143. Acceleration. The word *accelerator* has grown more and more common with the increased use of the automobile. A man is driving at a velocity or speed of "30 miles per hour." He presses the accelerator, and increases his velocity to "40 miles per hour." He has *added to* his velocity "10 miles per hour." Such an *increase in velocity is called acceleration.* When a manufacturer advertises that his car will "accelerate from 5 miles per hour to 25 miles per hour in 8 seconds," he means that in 8 seconds 20 miles per hour can be added to the velocity of the car. That is an addition, or acceleration, of 2.5 miles per hour per second. A body that moves 1 ft. the first second, 3 ft. the next second, 5 ft. the third second, etc., furnishes an example of *accelerated motion.* In each second the velocity *increases* 2 ft. per sec., hence we say that the acceleration is 2 ft. *per second per second.* If a car moves 1 mi. per hr. the first second, 3 mi. per hr. the next second, and 5 mi. per hr. the third second, the increase in velocity for each second is 2 mi. per hr.; the acceleration is 2 mi. *per hr. per second.* Since in both of the examples given the acceleration is constant, the motion is *uniformly* acceler-

ated. A body that moves 2 ft. the first second, 5 ft. the next second, and 10 ft. the third second is also an example of accelerated motion, but the acceleration is *not uniform;* it is *variably* accelerated motion, a type too common when some persons start cars in which others are riding.

In stopping a vehicle, it may move 7 ft., 5 ft., 3 ft., and 1 ft. in each of four *successive seconds.* This is an example of *negatively accelerated* motion. It is also known as *retarded* or *decelerated* motion. Since in each second 2 ft. per second are *subtracted* from its velocity, its motion is *uniformly* retarded.

Fig. 182. — Leaning tower at Pisa. (*Courtesy of Popular Science Monthly.*)

It is of interest to inquire what would happen if the acceleration stopped at the end of any *particular* second. A car in starting moves 5, 10, 15, and 20 feet per second for four successive seconds. The acceleration ceases at the end of the fourth second. Neglecting friction, the car still continues to move at the *uniform* velocity of 20 feet per second. In accelerated motion, where the velocity varies each second, *the velocity at the end of any second is equal to the distance the body would move during the next second, if at that instant it ceased to be accelerated.*

144. Laws of Accelerated Motion. Galileo made a large number of experiments with falling bodies. He dropped objects of different material from the top of the leaning

tower at Pisa and found that they all reached the ground at nearly the same time. (See Fig. 182.) Even paper fell rapidly when rolled into a compact ball. He used an inclined plane also to study the laws of falling bodies. A ball rolls down an inclined plane with uniformly accelerated motion, but the distance traveled in any number of seconds is so much less than that of freely falling bodies, that the distance can be more easily measured. (See Fig. 183.)

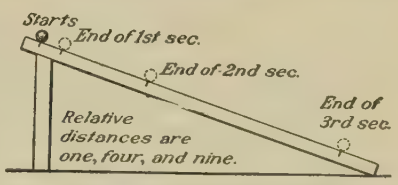


FIG. 183. — The ball gains velocity as it rolls down the plane.

If we were to repeat his experiments by letting a ball roll down a grooved plane which is made just steep enough so the ball rolls 1 ft. the first second, we should obtain results about as follows:

Ball rolls 1 foot in 1 second;
4 feet in 2 seconds;
9 feet in 3 seconds;
16 feet in 4 seconds;
25 feet in 5 seconds.

Thus we see that the distance the ball rolls is directly proportional to the square of the number of seconds. It is also easy to deduce the following observations:

The ball rolled 1 foot the *first* second;
3 feet the *second* second; (4–1)
5 feet the *third* second; (9–4)
7 feet the *fourth* second; (16–9)
9 feet the *fifth* second. (25–16)

The figures 1, 3, 5, 7, and 9 show that the motion was *uniformly* accelerated; the acceleration a is 2 feet per second for each second of time. Since velocity is the rate a body moves in a given time, and acceleration the change in rate for a given time, it is correct to use the term acceleration per second per second (rate of change of velocity per second),

or acceleration per hour per hour. To avoid apparent repetition, the expression "acceleration per second" will be used in this text when both the velocity and acceleration are rated in seconds. When a body starts from rest and travels with uniformly accelerated motion, *the acceleration equals twice the distance traversed during the first second.*

The *initial* velocity of the ball was zero; its acceleration, or gain in velocity, was 2 ft. per sec.; therefore its velocity at the *end* of the first second was 2 ft. per sec. At the end of the next second, its velocity was 4 ft. per second. In five seconds, 5×2, or 10 ft. per sec. will have been added to its original velocity. Its velocity at the end of the fifth second is 10 ft. per sec. Thus we find that in each case, the final velocity is equal to the *product of the acceleration by the time.*

From the simple observations given above, it is possible to deduce several laws that apply to all cases of uniformly accelerated motion.

Law 1. *If the acceleration is uniform, the velocity at the end of any second is directly proportional to the time.*

Using v to represent *final* velocity, a to represent acceleration, and t to represent time, we may express this statement algebraically; *final velocity equals acceleration times the time.*

$$v = at. \qquad \text{(Formula 1)}$$

In all types of motion, the total space passed over, S, equals the *average* velocity times the number of seconds, t; or, *distance = average velocity × time.*

The average velocity for any given number of seconds equals one half the sum of the initial and final velocities, or average velocity $= \frac{\text{initial velocity} + \text{final velocity}}{2}$. For a body starting from rest the initial velocity is zero; the final velocity equals at; from these values the second law may be derived:

$$\text{average velocity} = \frac{\text{zero} + at}{2},$$

whence we get by substitution in the formula, distance = average velocity × time, the following:

$$\text{distance} = \frac{at}{2} \times t, \text{ or } S = \tfrac{1}{2}at^2. \quad \text{(Formula 2)}$$

LAW 2. *If the acceleration is constant, the distance traversed in any given number of seconds is equal to one half the acceleration times the square of the number of seconds.*

In solving problems, we may use formula (1) to find v, a, or t, if two of these quantities are known. If any two of the following, a, t, and S, are known, the third may be found by the use of formula (2). Given a, v, and S; any two of them known, and the third to be found. Solving formula (1) for t, and substituting in formula (2) the value thus obtained, we get $v = \sqrt{2aS}$. (Formula 3)

The formula, $s = \frac{1}{2}a(2t-1)$, may be used to find the distance traversed in any *given* second, the *sixth* or *eighth*, for example.

PROBLEM. A ball starting from rest rolls down an inclined plane with uniformly accelerated motion. If its acceleration is 20 ft. per second per second, find: (1), its velocity at the end of the tenth second; (2), the distance it travels in 10 seconds; and (3), the distance it rolls in the eighth second.

Solution. To find the final velocity, we use the formula, $v = at$. Whence, $v = 20 \times 10$, or 200 ft. per second. By substituting in the formula, $S = \frac{1}{2}at^2$, the values for a and t, we have $S = \frac{1}{2} \times 20 \times (10)^2$. Whence $S = 1000$ ft. To find the distance the ball rolls in the eighth second, we use the formula $s = \frac{1}{2}a(2t-1)$. Whence $s = 10\ [(2 \times 8) - 1]$. $s = 150$ ft.

145. Retarded Motion. These laws and formulas also apply to retarded motion. Suppose we desire to find how far a car, traveling 30 mi. per hr., or 44 ft. per sec., will run before it can be stopped by the brakes, if they are capable of retarding the car 10 ft. per second. The problem is the same as if we asked how far a car must travel to attain a speed of 30 mi. per hr., if the acceleration is 10 ft. per second.

Solution. Velocity and acceleration are known; distance is to be found. These three quantities all occur in formula (3).

$v = \sqrt{2aS}$. (Formula 3)

$44 = \sqrt{2 \times 10 \times S}$, by substitution.

$20S = (44)^2$, and S equals 96.8 ft.

The chart in Fig. 184 shows the distances within which a car should be able to stop when traveling at different velocities. The student should observe that it needs 4 times the distance when the velocity is doubled.

146. Freely Falling Bodies. If we make the plane used in repeating Galileo's experiments steeper, the acceleration increases. When the plane is vertical, the ball becomes a freely falling body. The acceleration is due to the continu-

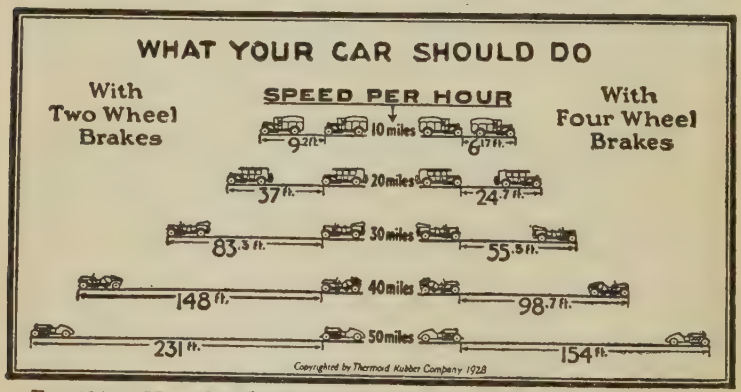


FIG. 184. — Note that *doubling* the velocity makes it take *four* times the distance needed to stop.

ous attractive force of gravity, but now it is not resolved into two components as before. (See Fig. 147, section 127.) The force of gravity pulls directly upon the ball.

We have learned that the "gram of force," which is a gravitational unit, imparts to 1 gm. of mass a velocity of 980 cm. per second in one second of time. Since $v = at$, then, from the above definition, a is equal to 980 cm. per second

at the latitude of New York. The laws of accelerated motion apply to freely falling bodies, but since the *acceleration due to gravity* is always the same at a given locality, the letter g is used instead of a to represent acceleration. For New York, $g = 980$ cm., or 32.16 ft. per second. The formulas derived in § 144 then become,

$v = gt$ (1); $S = \frac{1}{2}gt^2$ (2); $v = \sqrt{2gS}$ (3); $s = \frac{1}{2}g(2t-1)$ (4).

147. Objects Fall at the Same Rate in a Vacuum. When Galileo performed his celebrated experiments with falling bodies, he found that dense objects fell rather more rapidly than lighter objects. There was so little difference in the majority of cases that he concluded the unequal rate must be due to the resistance of the air, and *that all bodies would fall at the same rate in a vacuum.*

The invention of the air pump made it possible to prove the correctness of Galileo's theory. A long glass tube, containing a feather and a coin, is inverted. The feather flutters down slowly, striking the bottom at a considerable interval after the coin. (See Fig. 185 *A*.) When the air is pumped from the tube and it is again inverted, both fall simultaneously, Fig. 185 *B*. A man who weighs 200 lb. does not fall any faster than a man who weighs only 140 lb. A laboratory device known as the water hammer is sometimes used to demonstrate rapid fall in a vacuum. It consists of a glass tube partly filled with water; the air is removed and the tube sealed. When the tube is jerked suddenly, the water falls like a stone, producing a sharp click as it strikes the glass.

FIG. 185.—Bodies fall at same rate in vacuum.

148. Bodies Projected Upward. An object thrown upward is uniformly retarded until it finally stops rising. Then as it falls it is uniformly accelerated. If we know the initial

velocity with which it is projected upward, we may apply the laws of accelerated motion to find how high it will rise, and how long a time will be required for the ascent.

PROBLEM. An object is projected upward with a velocity of 100 m. per sec. How high will it rise? How long a time will be needed for the ascent? How long a time will elapse before it strikes the earth?

Solution. In the formula, $v = \sqrt{2gS}$, v and g are known; $g = 980$ cm. per sec., or 9.8 m. per sec. Substituting, $100 = \sqrt{2 \times 9.8 \times S}$, whence $S = 510.2$ m. From the formula, $v = gt$, we find the time required for the ascent, since v and g are known. Substituting, $100 = 9.8t$; whence $t = 10.2$ sec. Since it takes the same time for it to fall, it will be 20.4 sec. before it strikes the earth.

QUESTIONS

1. Why does a parachute descend so slowly?

2. Give a reason why you would expect an object at the top of a tall mountain to fall more rapidly than at its base. Give a reason why you would expect it to fall less rapidly.

3. Does the speedometer of an automobile show velocity or acceleration? Explain.

4. Since the earth's attraction for a 5-lb. iron weight is five times as much as it is for a 1-lb. iron weight, why does not the 5-lb. weight fall five times as fast?

5. Water is poured from a pitcher at a height of a foot or more. Explain why the stream of water becomes much reduced in size as it falls.

PROBLEMS

In solving problems pertaining to freely falling bodies, use $g = 980$ cm., or $g = 32$ ft.

1. An airplane travels at a velocity of 100 mi. per hr. Express its velocity in ft. per sec.

2. Chamberlain and Levine covered 3905 miles in a trans-oceanic flight of $46\frac{1}{2}$ hours. Find their average velocity in miles per hour.

3. In a motor-paced race, a bicycle rider covers 40 mi. in 55 min. Find his velocity in mi. per hr., and in ft. per sec.

4. The rear wheels of a car have a diameter of 35 in. and they make 400 revolutions per minute. Find the velocity of the car in miles per hour, and in feet per second.

5. A man runs 100 yd. in 10 sec. At that rate how long will it take him to run a mile? 2 min 56 seconds,

6. A train 200 yd. long runs 60 mi. per hr. How long will be required for it to pass completely over a bridge 680 ft. long? 14.54

7. How far does a body fall in 10 sec.? With what velocity does it strike the earth?

8. How far does a body fall in 4 sec.? In $\frac{1}{2}$ sec.? In $\frac{1}{4}$ sec.?

9. How far does a body fall in 7 sec.? In the seventh second? Solve the latter part by two methods.

10. A bomb is dropped from a dirigible at a height of 10,000 ft. How long will it take for the bomb to reach the earth?

11. A baseball is dropped from the top of Washington Monument, 504 ft. With what velocity does it strike the earth? Do you think it is possible for a player to catch a baseball moving at this velocity? Has the feat ever been accomplished?

12. With what velocity must a ball be thrown upward to make it rise to the top of the Woolworth building? (About 800 ft.)

13. An automobile running 20 mi. per hr. can stop in exactly 25 ft. What is the shortest distance in which the same car traveling 40 miles per hr. can be brought to a stop?

14. For brake tests used in some cities an automobile traveling 20 mi. per hr. must be brought to a stop within 34 ft. What is the minimum retardation of the brakes needed? How long will it take the driver to stop the car?

15. A train is running 60 mi. per hr. If the maximum retardation of the brakes is 5 ft. per sec., can the engineer stop the train within 600 ft?

16. An airplane traveling 100 mi. per hr. drops a bomb from a height of 3600 ft. How long will it take for the bomb to fall? With what velocity will it strike the earth? How far beyond the vertical line from which it was dropped will it strike the earth? (Consider that the bomb continues to move forward with a speed of 100 mi. per hr. as it falls.)

17. An object is thrown upward with a velocity of 80 m. per sec.

How high will it rise? How long will it be before it again reaches the earth?

18. The Eiffel Tower is about 300 m. high. With what velocity must an object be thrown upward to rise to the top of the tower? How long will it take to make the ascent?

B. THE PENDULUM.

149. The Pendulum. A pendulum is a body so suspended that it can swing to and fro about a horizontal axis. A simple pendulum is defined as a particle suspended by a weightless cord. Of course it is impossible to construct such an ideal pendulum, but a ball suspended by a light thread, as shown in Fig. 186, is essentially a simple pendulum. The point or axis about which a pendulum vibrates is called the *center of suspension.* As the ball moves from A to B it makes a *single vibration.* In moving from A to B and returning again to A, it makes a *complete vibration.* The time required for a complete vibration is known as the *period* of the pendulum. The angle AOC is called the *amplitude* of vibration.

FIG. 186. — Simple pendulum.

150. Laws of the Pendulum. The student will recall that it was Galileo who began the experiments on air pressure that were later finished by Torricelli. Next we met this genius dropping objects of different density from the top of the leaning tower at Pisa. These simple experiments led to others from which Galileo developed the laws of accelerated motion and falling bodies. Now we see this philosopher as he sits in the cathedral in Pisa and watches a chandelier as it swings to and fro. With one finger on his pulse, he finds that successive vibrations are made in equal times. Later he performed a series of experiments by means of which he ascertained several facts concerning the vibra-

tions of the pendulum. These facts are known as the LAWS OF THE PENDULUM.

1. *The time of vibration is independent of the weight or material of the pendulum.* This law is strictly true only if the pendulum vibrates in a vacuum. The air resistance has more effect upon a ball of cotton used as a pendulum bob than it does upon a ball of lead.

2. *The time of vibration is independent of the amplitude, if the arc is small.* A pendulum usually swings through an arc of 10° or less.

3. *The time of vibration is directly proportional to the square root of the length of the pendulum.* This law may be expressed algebraically as follows:

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

If we have two pendulums, one 25 cm. long and the other 100 cm., the longer one will vibrate just half as fast as the shorter one. The square roots of 25 and 100 are 5 and 10 respectively. Hence the times required for one vibration are in the ratio of 5 to 10, or 1 to 2.

4. *The period of vibration is inversely proportional to the square root of the acceleration due to gravity.* A pendulum vibrates rather more rapidly at the North Pole than at the equator. If we use the letter l to denote the length of a pendulum, and g to denote the acceleration due to gravity, then t, the time required for a single vibration, may be found by the following formula: $t = \pi\sqrt{\frac{l}{g}}$.

PROBLEM. Find the length of a pendulum that will make a single vibration in one second when g equals 980 cm. per second.

Solution. Substituting the values, $t = 1$, and $g = 980$ cm., in the formula $t = \pi\sqrt{\frac{l}{g}}$, or $t^2 = \frac{\pi^2 l}{g}$, we have $1 = \frac{9.86965\,l}{980}$, or $9.86965\,l = 980$ cm. Whence $l = 99.29$ cm., the length of a pendulum which

will vibrate seconds at the Latitude of New York, where $g = 980$ cm. per sec.

151. Center of Oscillation. The length of the pendulum shown in Fig. 187*a* is measured from the point of suspension to the center of gravity of the ball *B*. A meter stick *CD* suspended from one end by a hook, although apparently of the same length as the pendulum *a*, does not vibrate at the same rate. It is a *compound* pendulum, Fig. 187*b*. Since its weight is distributed along its length, the several parts tend to vibrate as pendulums of different lengths. The particles near the lower end would, if isolated from the rest, vibrate more slowly. It is possible to find an intermediate particle, however, that would vibrate at the same rate as the undivided meter stick. This particle is at the *center of oscillation*. Experiment shows that the meter stick will vibrate at the same rate as the simple pendulum *P*, which is $\frac{2}{3}$ its length. If we bore a hole through the meter stick at the center of oscillation and suspend the meter stick from this point, it will have the same period as before. The real length of the meter stick swinging as a pendulum is the distance between the center of suspension and the center of oscillation.

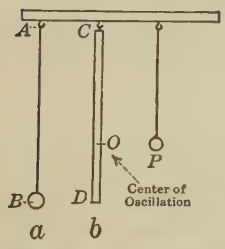


FIG. 187. — Compound pendulum.

152. Center of Percussion. If we strike the meter stick at its center of oscillation with a mallet when it is suspended as in Fig. 187*b*, it will swing smoothly as a pendulum, without being jarred. If the meter stick is struck at any other point, it shivers or trembles instead of vibrating freely. The center of oscillation is coincident with the *center of percussion*. The center of percussion of a body

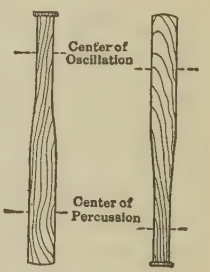


FIG. 188. — Center of percussion.

is that point where a blow produces the least effect upon the center of suspension. A baseball player can drive a ball harder and farther if it strikes the bat at the center of percussion. If the ball strikes the bat at any other point, the bat "stings" the hands and is more apt to be broken. (See Fig. 188.)

Sometimes the handle of a hammer or ax is made too big for the weight of the head or blade. A woodsman, testing an ax that has too much wood in the handle says the ax is poorly hung.

FIG. 189. — Clock pendulum.

153. Uses of the Pendulum. The chief use of a pendulum is for keeping time. In a clock the movement of the hands is controlled by the swinging of a pendulum. In Fig. 189 the escapement wheel *W* is one of a train of gear wheels that move the hands. While these wheels are driven by a weight or spring, yet the escapement wheel is released one cog at a time by the vibrating pendulum, which thus indirectly controls the movement of the hands. A slight push from each cog as it escapes keeps the pendulum vibrating. A pendulum can be used to measure altitudes, but the barometer is more convenient.

C. NEWTON'S LAWS OF MOTION

154. Newton's Laws of Motion. Sir Isaac Newton formulated three laws of motion that help to explain some very important principles of physics. While they are not capable of complete demonstration, yet observation and experiment furnish evidence of their truth as applied to the motion of both terrestrial and celestial bodies. We have already seen *how* bodies move; NEWTON'S LAWS explain *why* bodies move. They deal with the relation between force and motion.

155. Newton's First Law. *Every body continues in its state of rest or uniform motion in a straight line unless it is compelled by some external force to change that state.* This law is really a statement of the property of inertia, which was discussed in § 13. No inanimate body can move or stop moving. A horse must pull very much harder to start a heavy load than to keep it moving; when started, however, it continues to move unless a backward force is applied to stop it. That an object tends to continue in motion in a *straight* line is clearly shown by the fact that mud flies from a rapidly rotating carriage wheel, or water from a grindstone along a line tangent to the circumference. If ice offered no resistance by friction, one who starts to slide on a lake of ice would continue to slide in a straight line entirely across the lake. Automobile drivers in rolling country sometimes coast down one hill and the inertia of the moving car will carry it part way up the hill on the opposite side of the valley. The practice, however, is dangerous.

156. Momentum. The student may place one hand flat on the table and lay a 1-lb. weight upon it. The effect is not unpleasant, but he may not care to continue the experiment by lifting the weight to a height of a foot or more and dropping it upon his hand. The impact in the second case is due to the *momentum* of the weight, or the product of its mass times its velocity. A ferry-boat in docking moves very slowly, but a foot caught between the slowly moving boat and the dock would be crushed by the momentum of the boat. *This momentum is equal to the mass of the boat times its velocity.* A rifle bullet has terrific impact because its velocity is from 1500 to 3000 ft. per second, and its small weight of a few ounces multiplied by such high velocity gives a large momentum. A mass of 1 gm. moving with a velocity of 1 cm. per sec. has one unit of momentum (C.G.S.). A mass of 1 lb. moving with a velocity of 1 ft. per sec. has one unit of momentum (F.P.S.). A 2000-ton

boat moving with a velocity of 20 ft. per sec. has a momentum of 80,000,000 units.

157. Second Law of Motion. Newton's first law states what happens to matter when forces *do not act* upon it; his second law is a statement of what does happen when forces *do act* upon it. If a force of 1 lb. acting upon a body produces a certain acceleration, a force of 2 lb. will produce double the acceleration. The second law may be stated as follows: *Rate of change of momentum is directly proportional to the acting force, and takes place in the direction in which the force acts.* The latter part of this statement is obvious, since experience teaches us that motion takes place in the direction of the force which produces it. If a ball thrown with a given force moves with a velocity of 50 ft. per second, the force must be doubled to make the ball move with a velocity of 100 ft. per second. From this law of motion, we may modify our definition of the dyne. *It is that force which, acting for one second upon any mass, imparts to it unit momentum.*

When two or more forces act together, each produces its own change of momentum, independently of the other forces. Thus the force that drives a bullet in a horizontal direction acts continuously; at the same time the force of gravity is gradually pulling the bullet toward the earth. A ball dropped from the top of a tall tower strikes the ground at the same instant as a bullet fired horizontally from the top of the tower, although the latter may fall several thousand feet distant. (See Fig. 190.)

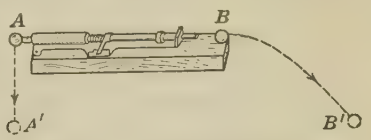


FIG. 190. — Both balls strike the floor at the same instant.

158. Path of a Projectile. (*a*) *Fired horizontally.* Many persons have the idea that a rifle bullet fired horizontally travels in a straight line, but such is not the case. Gravity

acts upon it immediately and constantly, pulling it from its course. Suppose its velocity is 3000 ft. per sec.; at the end of the first second, air resistance being ignored, it will have traveled 3000 ft.; but in 1 second a body falls 16.08 ft., and the bullet would strike 16.08 ft. below the point at which it was aimed. In 2 seconds the bullet travels 6000 ft., but it drops in the same interval 64.32 ft. (See Fig. 191*A*.) Of course, the greater the velocity, the more nearly the curve approaches a straight line. The curve of Fig. 191*B* shows the path of a ball thrown with a horizontal velocity of 100 ft. per second.

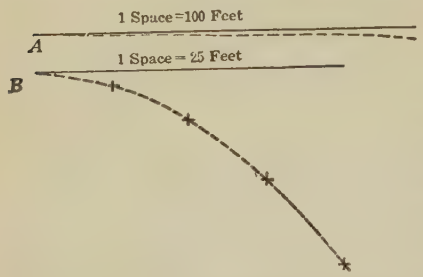


FIG. 191. — *A*. Curve of high velocity projectile. *B*. Curve of low velocity projectile.

(*b*) *Fired at an angle.* In the use of the modern rifle, in which the bullet may have a velocity of 3000 ft. per second, the path of the bullet is so nearly horizontal that no correction need be made for *short* distances. When the object is more remote, the rear sight of the rifle is raised a trifle. When the rifle is then aimed at an object, the end of the barrel is raised slightly. The farther away the object, the more the rear sight is elevated before taking aim. The muzzle of a field gun is always elevated so that the projectile is fired at an angle. Fig. 192 shows the path such a projectile may take. The angle *BAC* is the *angle of elevation*. *AC* and *AD* are the component horizontal and vertical velocities, and *AR* is the *range*. The path *ABR* is called the *trajectory*. The higher the velocity of the projectile, the flatter the trajectory, Fig. 191. Under actual conditions, air resistance

FIG. 192. — Path of projectile, fired at an angle.

reduces the range, and corrections must be made for windage.

At a disarmament conference held in Washington, the three nations, England, the United States, and Japan, agreed to a 5, 5, 3 ratio of first-class fighting ships. Later when some of our naval engineers proposed to remount the guns on our ships to permit them to be fired at a greater angle of elevation, England protested that such a change would increase the range of these guns and violate the spirit of the treaty. President Coolidge considered their protest well-founded, and the mounting was unchanged.

159. Composition of Velocities. From a consideration of the preceding paragraphs it is evident that we may have composition of velocities as well as composition of forces. Since it requires force to produce velocity, and we know that forces can be represented graphically, it seems reasonable to believe that velocities can be plotted in the same manner. In fact we can not only plot velocities, but we can also determine the resultant of two or more velocities acting concurrently. If a man rows a boat across a stream at a velocity of 4 miles per hour, and the current carries the boat down stream with a velocity of 4 miles per hour, we can find the *resultant* velocity by drawing the parallelogram shown in Fig. 193, and calculating the length of the diagonal. If the stream were 4 miles wide, the man would row across in an hour, but he would land 4 miles downstream, unless he kept the bow pointed somewhat upstream. He would actually have traveled along the diagonal of the parallelogram a distance of 5.66 miles ($\sqrt{(4)^2+(4)^2}=5.66$).

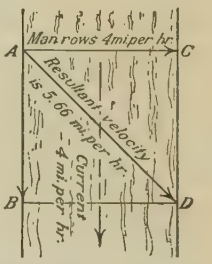


FIG. 193. — Concurrent velocities.

160. Newton's Third Law. A boy rows a boat toward the shore of a lake. When he is 3 or 4 feet from shore, he steps

on the bow and attempts to leap ashore. The force with which he impels himself forward reacts and pushes the boat backward. The boy misses his mark and falls into the water. One who wishes to jump forward must stand on something fixed which resists this acting force. The end of a garden hose lying on the lawn is pushed backward by the reaction of the water as it issues from the nozzle. Water reacts against the oars of a boat and the arms of a swimmer; its reaction against the propellers makes the movement of a steamboat possible. The reaction of the air against the wings of a bird enables it to fly. The air reacts against the propellers of an airplane as they drive the plane forward, and the reaction against the plane is resolved into two components, one of which lifts the plane. (See Fig. 157.)

Fig. 194. — Action equals reaction.

If we fasten one spring balance to the table, hook another spring balance to it as shown in Fig. 194, and pull steadily, it may be shown that the *reaction is equal to the action.* Both balances show the same reading. The collision balls of Fig. 195, may also be used to show that the force of reaction is *equal* to the action. If one ball is raised and let fall, one ball flies out at the opposite end of the line. When two balls are let fall, two balls at the other end of the line move in response to their action. Newton's third law is usually stated as follows: *To every action there is an equal and opposite reaction.*

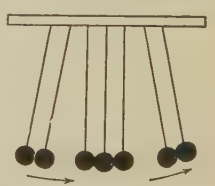


Fig. 195. — Action equals reaction.

Some have tried to argue that no motion can occur, if action and reaction are equal. But in reaction *two different* bodies are always involved. The water against the oars, the air against the propeller, etc. But if two boys pull upon a light wagon in opposite directions, the wagon moves in the direction of the greater force. Here *two forces* act upon *one*

body. This is an example of *counteraction*, in which there is an *unbalanced* force. *Reaction* is shown by the fact that the earth reacts against the feet of each boy with a force which is exactly equal to the pull he exerts. The driving wheels of a moving automobile push backward on the ground, but the ground pushes forward on the wheels. This is reaction, but when this car tows another car the pull on the tow-line is an unbalanced force.

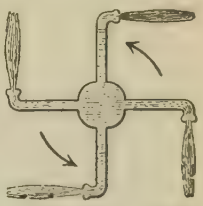


FIG. 196. — Water reacts against the nozzles.

161. Applications of Reaction. We have already seen that reaction makes flying, swimming, rowing, etc., possible. The *rotary* lawn sprinkler works on the same principle. (See Fig. 196.) As the water issues from the nozzles, the rotating head is turned backward, thus scattering the water in all directions. The pin-wheel as used in fireworks is turned in the same manner. The "kick" or recoil of a gun is an example of reaction. The recoil is sometimes used to eject the empty cartridges in rapid-fire guns. In

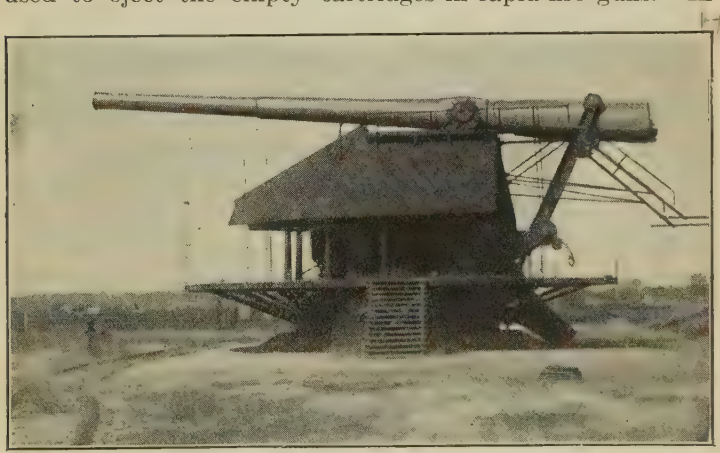


FIG. 197. — This disappearing gun can hurl a 16-inch projectile through 14 in. of armor plate steel. Its recoil energy is 4000 foot-tons. The gun, which is 70 ft. long, is mounted in a "barbette" housing. (*Times Photo.*)

the *disappearing* guns used for coast defense, the recoil of the gun carries the gun back on its carriage and down behind the fortifications. (See Fig. 197.) Ordinary walking is possible because the earth pushes forward against us as hard as we push backward.

D. CURVILINEAR MOTION AND CENTRIFUGAL FORCE

162. How Curvilinear Motion is Produced. From Newton's first law we learned that a body which has acquired velocity continues to move in a straight line. If a second force acts upon the moving body at right angles to its path, it will be deflected from its rectilinear line, and its motion will become curvilinear. To illustrate, we may tie one end of a string to a ball. Holding the other end firmly, we may swing the ball in a circle about the hand as a center. The pull of the hand upon the cord deflects the ball away from its rectilinear path and toward the center. (See Fig. 198.) As the ball moves along the circumference from B to A, the pull toward the center has deflected it a distance equal to AO. The constant pull that deflects a body from its rectilinear path and compels it to move along a curve, is called *centripetal* force (*centrum*, center; *petere*, to seek).

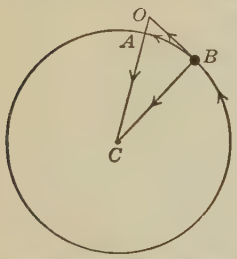


FIG. 198. — Curvilinear motion.

163. Centrifugal Force (*centrum*, center; *fugere*, to flee from). If the revolving body of Fig. 198 did not have inertia, it would be pulled to the center. If the earth in revolving around the sun did not have inertia, it would fall into the sun. The reaction due to the inertia of the moving ball offers resistance to the centripetal pull and tends to break the string. If the string breaks, the ball immediately begins to move in a straight line along a tangent to the curved path. *The resistance that a moving body offers to deflection from a*

straight line is commonly known as centrifugal force. Some physicists object to the use of the term "force" as applied to the tendency a body offers to resist being deflected from its path, but beginners find it easier to think of such reaction as *centrifugal force.*

164. Illustrations. Mud flies from a rotating carriage wheel when the centrifugal force exceeds its adhesion to the tire. Water flies off at a tangent from a rapidly turning grind-

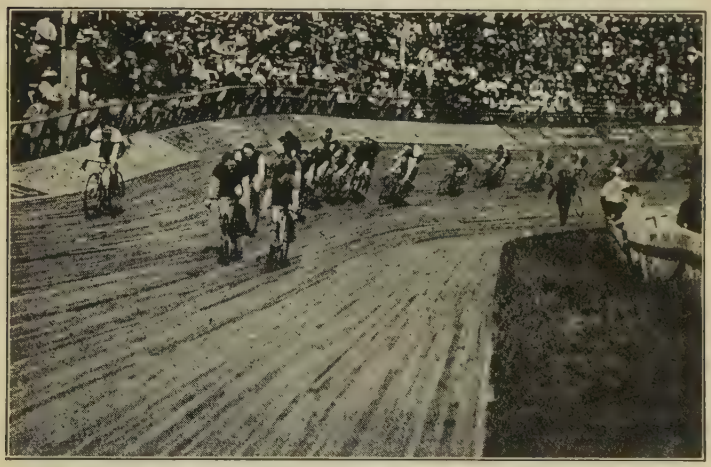
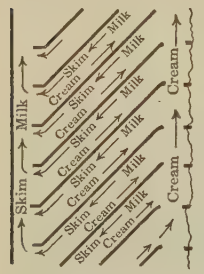


FIG. 199. — The Velodrome track at Newark, N. J., is banked at the turns to counteract centrifugal force.

stone. David knew that a high velocity could be imparted to a missile by putting it in a sling and whirling it around his head. That knowledge and his skill in controlling the direction of the stone which he picked out of the brook made him the conqueror of Goliath. Emery wheels sometimes burst when driven at high velocity; the centrifugal force exceeds cohesion. An automobile rounding a curve at high speed is apt to turn "turtle."

Then it quite often happens that some method must be used to counteract centrifugal force. For example, we lean

toward the center when skating around a curve. To prevent the overturning of a railway train rounding a curve, the track is banked so that the rails on the outside of the curve are higher than the inside rails. Roads for automobiles are now banked at the curves. Running tracks in gymnasia and race-tracks of all kinds are banked at the curves to help overcome centrifugal force. Fig. 199, shows one of the turns on the Velodrome track in Newark where bicycle and motor-cycle races are held.


Milk
Skim
Cream
Milk
Skim
Cream
Milk
Skim
Cream

James Watt devised a *governor* to regulate the speed of a stationary engine. It is operated by a belt driven from the shaft of the flywheel of the engine. As the speed increases, the two balls, Fig. 203, move farther apart, since centrifugal force increases with the speed. As they move outward, they lift one end of a lever which shuts off some of the steam. The reverse occurs when the engine begins to slow down.

Fig. 202. — Cream separator.

The *speedometer* of an automobile operates on a similar principle. Small weights are hinged to a shaft which is driven through a flexible cable by means of a gear attached to the drive shaft or to one of the wheels. As the speed increases these weights pull outward and move the pointer over a graduated dial.

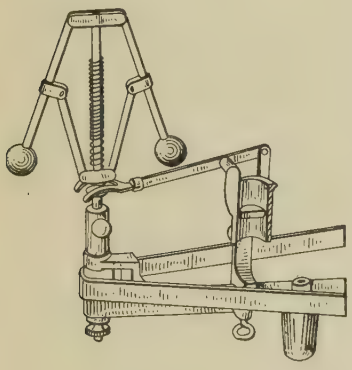


Fig. 203. — Centrifugal force regulates speed of steam engine.

Wet solids may be partially dried by putting them in a perforated cylinder, which is then rapidly rotated. The water is thrown out through the openings. Crystals are dried in this manner; laundries also use this method for drying clothes. (See Fig. 204.) Some types of electric washing machines use the centrifuge for drying clothes.

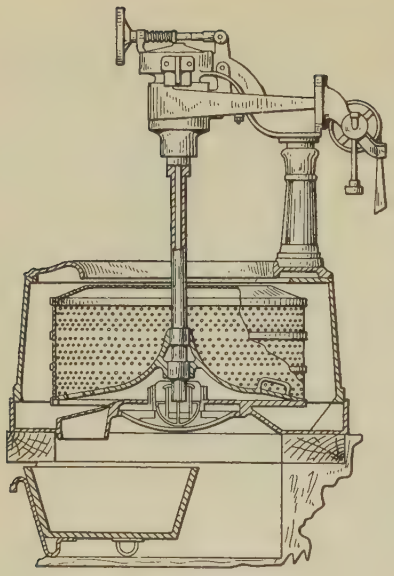


FIG. 204. — Centrifugals are used to dry clothes, crystals, etc.

A very efficient type of water pump depends for its action upon centrifugal force. (See Fig. 205.) As the rotor turns rapidly in the direction shown by the arrows, the water is forced by the rotating blades out through the discharge pipe.

Liquids that contain sediment are often centrifuged instead of being filtered. The sediment from varnish is removed by this method. In making artificial silk the solution of cotton must be passed through openings .005 mm. in diameter. As the solution of cotton flows into a solution of sodium hydroxide a fiber is formed. It takes 20 of the small fibers thus produced to make a single thread of the silk. Since these openings are so very minute, the solution is centrifuged at 8000 or 10,000 revolutions per minute before spinning, in order to remove any sediment that might clog the openings. (See Fig. 206.)

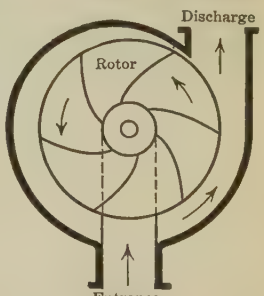


FIG. 205. — Centrifugal pump.

Even our amusement parks utilize centrifugal force. At Coney Island the "human pool table" is an example. The "whip," the "loop-the-loop," etc., are other examples.

166. Magnitude of Centrifugal Force. It is possible to measure the pull which the ball of Fig. 198, exerts upon the string. If we use a ball which has just double the mass, the pull on the string will be just twice as great. Hence we conclude that *the centrifugal force is directly proportional to the mass.* If we shorten the string, the ball is pulled from its path faster and it reacts with greater force to break the string. Careful measurements show that *centrifugal force is inversely proportional to the radius of curvature.* As we swing the ball faster, so that the velocity along the curve increases, it pulls more strongly on the cord. Accurate measurements show that the *centrifugal force is directly proportional to the square of the velocity.* If v = velocity in centimeters per second, m the mass in grams, and r the radius in centimeters, then

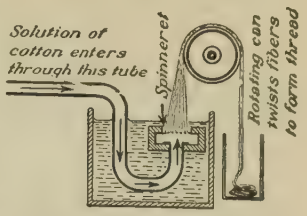


FIG. 206. — The solution of cotton forms a fiber as it flows into the caustic liquid.

$$\text{C.F. (in dynes)} = \frac{mv^2}{r}. \qquad \text{C.F. (in gm.)} = \frac{mv^2}{gr}.$$

In the English system, if mass is in pounds, radius in feet, and velocity in feet per second, then

$$\text{C. F. (in poundals)} = \frac{mv^2}{r}. \quad \text{C. F. (in pounds)} = \frac{mv^2}{gr}.$$

PROBLEM. A ball that weighs 10 lb. is being rotated by means of a cord 4 ft. long. If its velocity is 20 ft. per second, find the force in pounds that tends to break the cord.

Solution. v, g, r, and m are known. Substituting the values in the formula, C. F. $= \frac{mv^2}{gr}$, we get, C. F. $= \frac{10 \times (20)^2}{32 \times 4}$. Whence, C. F. = 31.25 lb.

167. The Gyroscope. Everyone is familiar with the toy gyroscope and the spinning top. The centrifugal force of a heavy, rotating wheel gives it great stability. When such a wheel is rotating rapidly in a certain plane, considerable force must be used to change the plane of rotation. The principle of the gyroscope has been put to practical use in many ways. The Sperry type of stabilizer used on airplanes depends upon this principle. A gyroscopic compass is now used on all submarines. In the monorail cars stability is secured by a pair of gyroscopic wheels rotating in opposite directions on axes that extend across the car. The flywheels on the engines of a steamship are mounted in this manner; thus they tend to prevent the rolling of the ship.

E. FRICTION

168. Friction *opposes any force trying to produce motion.* It is the resistance that opposes any effort to roll or slide one body over another. To some extent it is due to adhesion, but it is largely caused by irregularities in the surfaces of the bodies. Between smooth, plane surfaces the friction is much less than it is between roughened surfaces.

169. Advantages and Disadvantages of Friction. In all cases where an object is to be moved or a resisting force is to be overcome, friction is a disadvantage. An axle upon which a wheel must turn is highly polished and then oiled to reduce friction. In the bearings of a sewing machine, a bicycle, an automobile, or other machines, efforts are made to reduce friction to a minimum.

In many cases friction is an advantage. We see a driver try to start an automobile on icy streets. The rear wheels spin around but the car does not move. Friction between the tires and the pavement is needed to start the car. A horse cannot pull a load unless friction furnishes him a secure foothold. Without friction we would be unable to walk. The smoothest ice has some friction, but even then walking

is difficult. Without friction a nail or a screw, driven into a board, would not hold the board in place at all. A hook screwed into the ceiling would fall out of its own weight. The caterpillar tractor can pull heavy loads even over soft

FIG. 207. — The caterpillar tractor utilizes friction.

ground, because the projections increase friction. (See Fig. 207.)

170. Sliding Friction. By experiment several so-called laws of sliding friction have been developed. In most cases they are approximations, with many more exceptions than are common to most laws in physics. By use of a spring balance attached to a sliding object, it may be shown that *sliding friction is much greater at starting*, but that *it is nearly independent of velocity* when a body is in motion. To start a heavy load on a sled requires more effort than it does to keep it moving, but it will not be much less if one runs with the

sled than it is when he walks. A brick offers nearly the same resistance when sliding on its side that it does when sliding on its edge. *Sliding friction is practically independent of the area of contact between the surfaces,* unless the area of one surface is so small that it will cut into the other. It does not require so much force to slide an empty chair across the floor as it does if a 200-lb. man sits on the chair. *Friction is directly proportional to the weight of the object.*

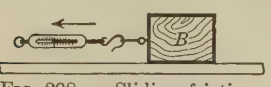


FIG. 208. — Sliding friction.

171. Coefficient of Friction. Let us weigh a block of wood and then hook a spring balance to it so the block may be pulled along the table. (See Fig. 208.) The reading of the spring balance is much less than the weight of the block. It takes less force to slide one end of a piano than it does to lift it. The ratio of this "force of friction" to the weight of the block is called the *coefficient of friction.*

$$\text{Coefficient of friction} = \frac{\text{force needed to overcome friction}}{\text{weight}}.$$

Suppose the block weighs 100 gm., and it needs a force of only 30 grams to keep the block in uniform motion. Then the coefficient of friction is $\frac{30}{100}$, or 0.3. The coefficient of friction varies with the nature of the material and the degree of polish of the surface. The coefficient of friction of iron sliding on iron is less than that of wood sliding on wood.

172. Fluid Friction. Everyone knows that an automobile "skids" more easily on a wet pavement than it does on one that is dry. We know that oil makes a machine run more easily. It is generally true that *fluid* friction is much less than *solid* friction. To show the difference one might try rowing a boat in the water and then try to row the boat over the sand on the beach.

While sliding friction is quite independent of velocity, fluid friction varies greatly with the velocity. At moderate speeds fluid friction is nearly proportional to the square of

the velocity; at higher speeds it is proportional to the cube of the velocity, or nearly so. The railroad companies charge a higher fare on fast trains because it costs more to operate them at high speed. The air resistance increases with an increase of velocity. It is estimated that a modern automobile traveling 40 miles per hour uses over 7% of its fuel energy in overcoming air resistance. The weight of a destroyer in the navy is only about one sixth that of one of our modern battleships, but its engines must develop nearly the same horse power because their speed is from 10 to 15 knots more per hour. The friction in plowing through the water increases rapidly with the increased speed. The *Mauretania* uses engines of 70,000 horse power, but some slower vessels

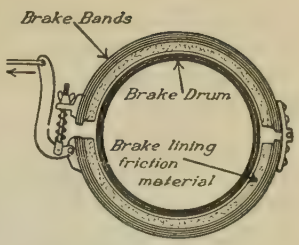


FIG. 209. — Brake bands are lined with friction material.

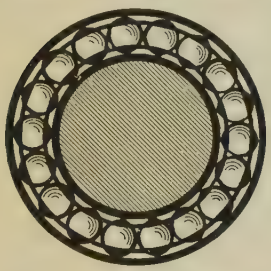


FIG. 210. — Ball bearings.

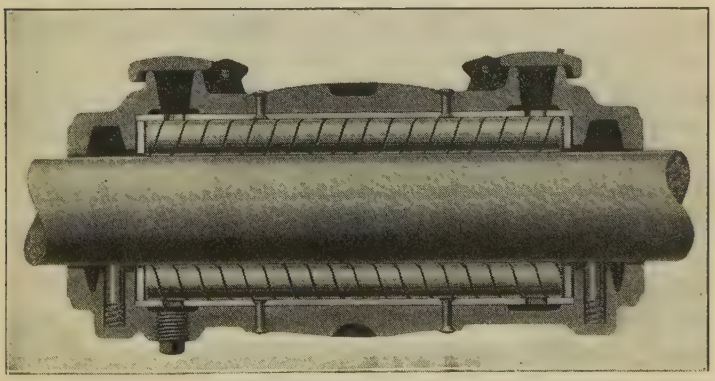


FIG. 211. — Flexible roller bearings. See also Fig. 755.

of equal displacement use engines of about half that horse power.

173. Methods of Increasing Friction. The engineer of a locomotive often sands the rails so the drive wheels will not slip. Chains are put on the rear wheels of automobiles to enable the tires to "grip" the pavement without "skidding." Sand is used on icy pavements, and our concrete roads are left with rough surfaces to increase friction. The brakes of automobiles are lined with material that has a high coefficient of friction. (See Fig. 209.)

174. Methods of Reducing Friction. Several methods of reducing friction are in common use. (1) The surfaces of bearings are made of highly polished material. (2) Bearings are often packed with Babbitt metal, an alloy that has a very low coefficient of friction. It is sometimes called antifriction metal. (3) Ball bearings, or roller bearings, are often used, since rolling friction is decidedly less than sliding friction. (See Figs. 210 and 211.) Rolling friction is especially low if both surfaces are hard. When one sinks into the other, as a carriage wheel into a sandy road, then rolling friction may be very great. A sled may slide over the snow more easily than a vehicle on wheels may be pulled through the snow. Fig. 212, shows how a wheel in soft earth encounters friction. Fig. 213, shows the tapered roller bearings which are used on many automobiles. They are especially strong in resisting sidewise thrusts. (4) *Lubricants* are used to reduce friction. Some of the most common lubricants are oils, grease, and graphite. Paraffin and soap are good lubricants for wood. When oil, for example, is used as a lubricant, an oil film flows between the surfaces of the bearings, sep-

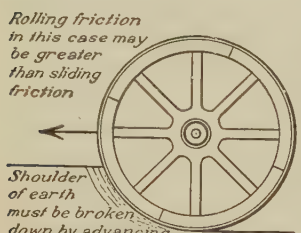

Rolling friction in this case may be greater than sliding friction
Shoulder of earth must be broken down by advancing wheel.

FIG. 212. — Rolling friction is great in such cases.

arating them so that fluid friction is substituted for solid friction. A good lubricant must have just body enough so that it will not be squeezed out of the bearing by the weight

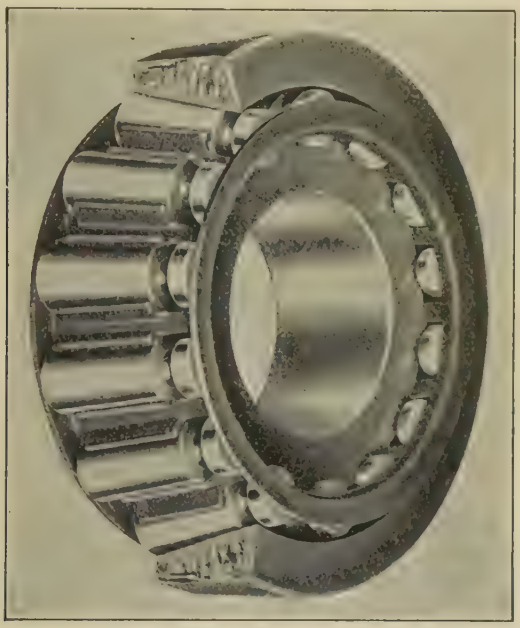


Fig. 213. — Tapered roller bearings. See also Fig. 767.

of the parts; it must not evaporate readily; it must not corrode the bearings; and it must be free from hard, gritty substances.

SUMMARY

Motion may be rectilinear or curvilinear. Velocity is the rate of motion. Acceleration is the rate of change of velocity.

If the acceleration is constant, velocity = acceleration $\times$ time; space passed over $= \frac{1}{2}\ at^2$.

The laws of accelerated motion apply to uniformly retarded motion. Freely falling bodies are uniformly accelerated. The

acceleration, which is due to gravity, is approximately 980 cm. per second.

The period of vibration of the pendulum is independent of the mass, material, or amplitude; it is directly proportional to the square root of the length, and inversely proportional to the square root of the acceleration due to gravity.

Newton formulated three laws of motion: Every body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to change that state. Rate of change of momentum is proportional to the acting force and takes place in the direction in which the force acts. For every action there is an equal and opposite reaction.

Momentum is the quantity of motion. It equals the product of the mass times the velocity.

Centrifugal force increases with the mass; it is directly proportional to the square of the velocity; it is inversely proportional to the radius of curvature.

Friction, or the resistance to motion, is generally greater in solids than in fluids. Lubricants are used to reduce friction.

QUESTIONS

1. If a clock gains time, would you raise or lower the pendulum bob? Explain.

2. Does a pendulum vibrate faster at the top of a mountain or at its base? Give a reason for your answer.

3. A string fastened to a hook can just support a weight of 50 lb. If two boys pull at opposite ends of this string when the weight is removed, how much must each pull to break the string? Explain.

4. Explain the principle of the rotary lawn sprinkler.

5. If action equals reaction, why is it not as dangerous to receive the "kick" of a gun as to be struck by the bullet?

6. Why is the head of a hammer tightened by pounding on the end of the handle?

7. Why do farm wagons often have tires from 3 to 5 inches wide?

8. How does centrifugal force affect the weight of objects at the equator?

9. A hammer sometimes "stings" the hand. Explain.

10. How would you locate the center of percussion of a baseball bat?

11. How do the bicycle and motor-cycle illustrate the gyroscopic principle?

12. Could David have thrown a stone farther with a 3-ft. or a 4-ft. cord attached to his sling? Explain.

13. If a man is strong enough to swing a 5-ft. baseball bat, can he drive a ball farther with it than with a bat of the usual length? If so, why not use such a bat?

14. Other things being equal, does a long-armed baseball pitcher have an advantage over his shorter-armed opponent?

15. What are the characteristics of a good lubricant? What kind would you select for the axle of a motor truck? For the wheels of your watch?

16. Why do automobile drivers use a different kind of oil in winter than that used in summer?

17. What do manufacturers mean by a "non-skid" tire?

18. What advantages does the "caterpillar" tractor shown in Fig. 207 have?

19. Why are jewels used in the bearings of high-grade watches?

20. To supply trains with water long shallow containers are sometimes placed between the rails. As the rapidly moving engine passes over these containers, a curved sheet of metal is lowered so that one edge dips into the water. Explain how the water gets into the tender of the engine. (See Fig. 4.)

PROBLEMS

1. If a pendulum 100 cm. long makes a single vibration in one second, how long will it take for a pendulum 64 cm. long to vibrate?

2. How long must a pendulum be to make a single vibration in 0.5 sec., if g equals 980 cm. per second?

3. If a force of 20 lb. keeps a 2000 lb. roller moving, what is the coefficient of friction?

4. What is the maximum pull that a 90-ton engine can exert, if the coefficient of friction between the drive wheels and the rails is 0.2? How much can the engine pull if the coefficient of friction is increased to 0.4 by sanding the rails?

5. A ball weighing 12 lb. is swung in a circle by a cord 4 ft.

long. If its velocity is 20 ft. per sec., what pull in pounds does it exert on the cord?

6. If a force of 20 lb. is needed to pull a sled weighing 200 lb. over the ice, what is the coefficient of friction?

7. Which has the greater momentum, a 175-lb man running with a speed of 25 ft. per second, or a 160-lb. man running with a speed of 30 ft. per second?

8. A car weighing 2400 lb. rounds a curve of 60 ft. radius at a velocity of 45 mi. per hr. What is the force tending to overturn it? What do you think will happen to the car?

9. If the car of the preceding problem rounds the curve at a velocity of 29 ft. per second (about 20 mi. per hour), what is the centrifugal force?

CHAPTER 7

WORK—POWER—ENERGY

A. WORK

Vocabulary

Force, a push or a pull.
Work, a force that moves a resisting body does work.
Power, the rate of doing work.

175. Work. *When a force acts upon a body in such a way that the body is moved, it is said to do work upon the body.* A man pulling at a 2000-lb. safe does no work unless he moves

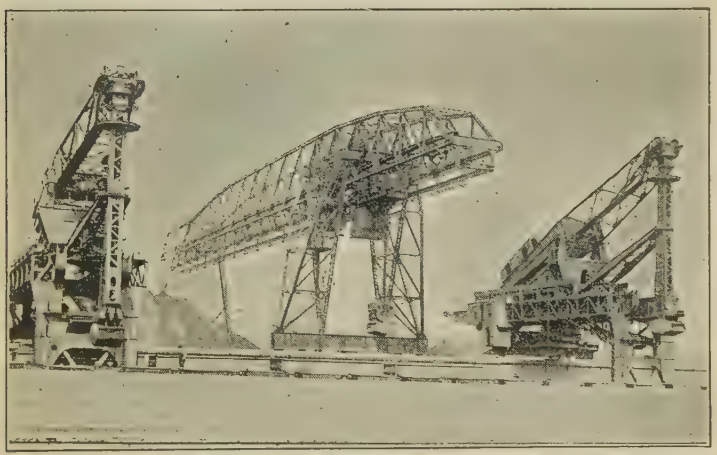


FIG. 214. — Gigantic cranes unload 10,000 to 13,000 tons of iron ore in four or five hours.

the safe. If a man holds a weight of 100 lb. on his shoulder all day, he is exerting force, but in the *scientific sense* he is not doing any work. He does work when he lifts the weight

to his shoulder. *The amount of work done is the product of the force times the distance through which it acts.* This definition of the term "work" is quite different from the usual conception of the word. Usually a man is not paid for his *effort*, but for the *effect produced*, or the *work accomplished.* A student is graded upon the task accomplished and not

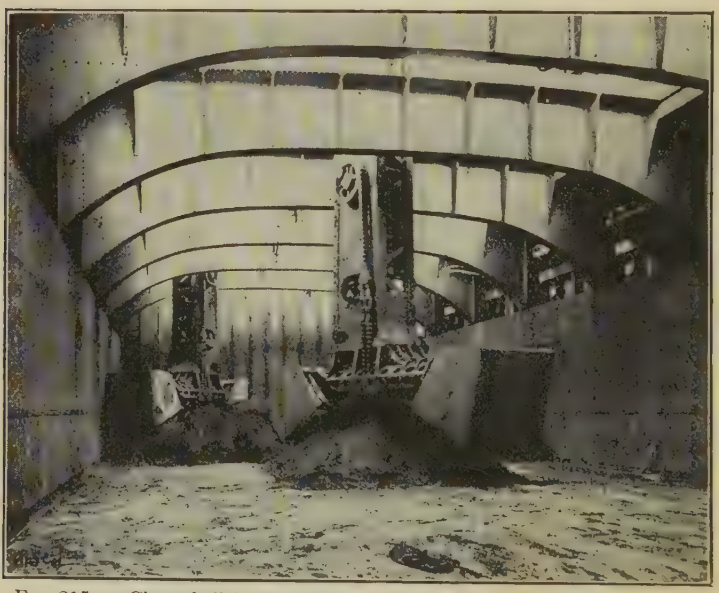


FIG. 215. — Clam-shell buckets of ore unloaders hold from 10 to 15 tons of ore.

upon his efforts. The ore crane shown in Fig. 214 works rapidly, since it can remove 15 tons of ore per bucketful. Boats containing 13,000 tons have been unloaded in $4\frac{1}{2}$ hours with the modern unloaders. (See Fig. 215.)

176. Units of Work. (*a*) *Gravitational units.* In the Metric system the gravitational units of work are the *gram centimeter* and the *kilogram meter*. The names practically define themselves. The gram centimeter is the amount of work

done by one "gram of force" when it moves the body upon which it acts a distance of one centimeter. The kilogram meter is the amount of work done by a force of one kilogram acting through a distance of one meter.

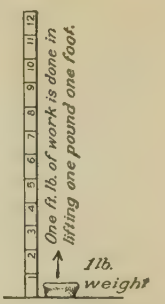


FIG. 216. — Work done in lifting a weight.

In the English System the *foot pound* is the gravitational unit. The foot pound is the amount of work done by one "pound of force" acting through a distance of one foot. (See Fig. 216.) A man weighing 160 lb. does 1600 ft. lb. of work in climbing a flight of stairs 10 ft. high. He lifts his own weight 10 ft. against the force of gravity. When an object is lifted *vertically*, the amount of work done always equals the *weight of the object* times the *vertical height* through which it is lifted. The reason for this is quite apparent, since one must use a force of 100 lb. in order to *lift* 100 lb. vertically. To *drag* a trunk weighing 150 lb. across a platform 20 ft. long, the amount of work done is not equal to the product of the weight and distance. The force in this case is smaller, since all that is needed is to overcome friction. If the coefficient of friction is 0.3, then the force required to keep the trunk moving is only 45 lb. The amount of work done in sliding the trunk through a distance of 20 ft. is equal to 45×20, or 900 ft. lb. (See Fig. 217.) To carry the same trunk up a flight of stairs 20 ft. high (measured vertically), one would do 150×20, or 3000 ft. lb. of work.

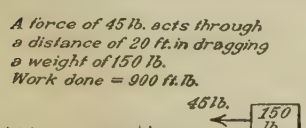


FIG. 217. — Work done in sliding a weight.

$$\text{Work} = \text{force} \times \text{distance}.$$

(*b*) *Absolute units.* Three absolute units of work are in

use; the *erg*, the *joule*, and the *foot poundal*. The *erg* is the amount of work done by a force of one dyne acting through a distance of one centimeter. It is really one *dyne centimeter*. Since the dyne is only $\frac{1}{980}$ of a gram, then the erg must be only $\frac{1}{980}$ of the gram centimeter. The erg is such a small unit that the *joule* is more often used. This unit is named in honor of a great English physicist, James Prescott Joule. It is equal to 10,000,000 ergs, or 10^7 ergs. The amount of work done by a force of one poundal acting through a distance of one foot is called a *foot poundal*. There are 32.16 foot poundals in one foot pound.

B. POWER

177. Power Defined. We know that *force* is independent of distance. In fact, the force is the same even if there is no motion at all. *Force is also independent of time.* On the other hand, *work* does depend upon both force and distance. If the distance moved is zero, no work is done. The amount of work done equals *force times distance*, but *it is wholly independent of time.* A man does the same amount of work when he climbs a flight of stairs in 1 minute that he does when he climbs the same flight in 5 minutes, but *he does not use the same amount of power. Power depends upon three factors: the force exerted, the distance it moves, and the time required.*

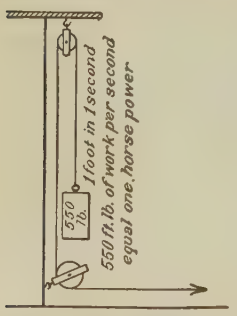


FIG. 218. — How horse power was determined.

In the study of power, the student must revise his conception of the meaning of the word "power." We are accustomed to speak of a "powerful" man when we mean that he is strong and capable of exerting great force. Such a man may work so slowly that his power in a scientific sense is very small.

178. Units of Power. In a series of experiments, James Watt, the inventor of the steam engine, found that an English dray horse could continue for a reasonable length of time to do 550 ft. lb. of work per second. More recent experiments show that the average horse has only about $\frac{3}{4}$ this power, but the value of the horse power is still based upon Watt's experiments. (See Fig. 218.) In the English system the *horse power* is the unit of power; it is equal to 550 ft. lb. of work *per second*, or 33,000 ft. lb. of work *per minute*. Engines in this country are rated in horse power,

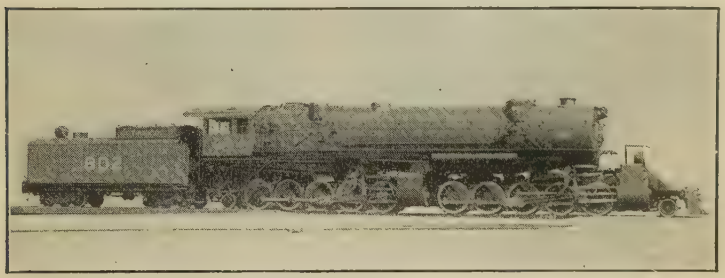
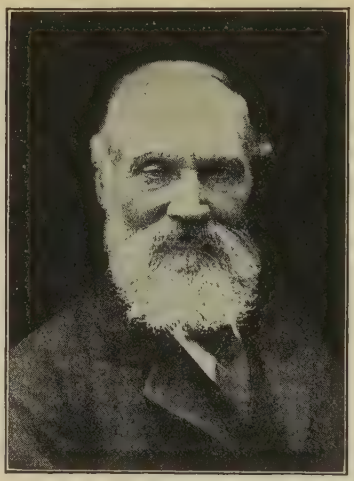


FIG. 219. — The Virginian locomotive is the largest in the world. During a test on May 25, 1921, this locomotive pulled a solid train of one hundred 120-ton gondola cars, loaded to capacity, a total weight of 16,000 gross tons. The engine weighs 450 tons; its horse power is 5100. It uses one ton of coal every ten minutes, the coal being fed by a mechanical stoker.

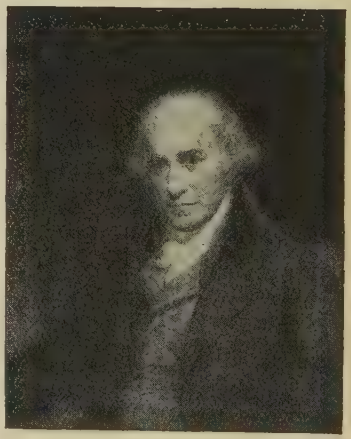
or in kilowatts. The ordinary railroad locomotive has a horse power of 500 to 1000. (See Fig. 219.) The power of the average man is about $\frac{1}{7}$ horse power; it is equal to about 78 ft. lb. per second.

The *watt* and the *kilowatt* are units of power used in the Metric system. *The watt is equal to one joule per second. The kilowatt (K.W.) equals 1000 watts.* The horse power (H.P.) is equivalent to 746 watts, or nearly $\frac{3}{4}$ of a kilowatt. For example, a 15 K.W. engine is approximately 20 H.P. A 100 H.P. engine (about 75 K.W.) can lift a car weighing 4000 lb. to a height of 825 ft. in one minute.



Sir William Thomson (Lord Kelvin) (1824–1907) was born at Belfast, Ireland. His most important contributions to physics were in heat and electricity. He invented the absolute scale of temperature. His other inventions include the mirror galvanometer, the siphon recorder for use in receiving cable signals, and an improved mariner's compass. Thomson combined mathematical ability with inventive genius.

James Watt (1736–1819) was a Scotch engineer. Watt is considered as the inventor of the steam engine. He improved the old Newcomen engine by adding valves to make it double acting, and by using an external condenser. His inventions include the centrifugal governor, the water and steam gauges, and the steam hammer. He made the first compound engine. The metric unit of power is called the watt in his honor.



PROBLEM. What horse power engine is required to hoist 100 tons of coal per hr. from a mine 200 ft. deep?

Solution. Horse power $= \dfrac{\text{total work done (in ft. lb.)}}{550 \times \text{time in seconds}}$.

Then, horse power $= \dfrac{100 \times 2000 \times 200}{550 \times 60 \times 60}$; the answer is 20.2 H.P.

PROBLEMS

1. How much work would you do in climbing a flight of stairs 20 ft. high? What is your horse power, if you run up the stairs in 10 seconds? Suppose you can climb the stairs in 10 seconds or less; would the results show that $\frac{1}{7}$ H.P. is too low an estimate for the average man power?

2. If a horse pulls with a force of 240 lb. to keep an 800-lb. wagon moving, how much work does he do in pulling the wagon $\frac{1}{4}$ mile? If he pulls the wagon at the rate of 2 mi. per hr., what horse power does he use?

3. If each of the citizens of a city of 400,000 inhabitants uses 5 gallons of water (40 lb.) daily, what H.P. engines must be used if the height to which the water must be pumped is 100 feet?

4. The express elevator in the Woolworth building makes the ascent to the tower in one minute. If the distance is 750 ft., what H.P. is used in lifting a 200-lb. man to the tower?

5. What H.P. would you use in climbing a mountain 2500 ft. high in 30 minutes? Since you could probably walk 4 times that far in 30 minutes, give a reason why mountain climbing is so slow and fatiguing.

6. A block of wood 4 ft. 6 in. long is 1 foot thick. Its weight is 400 lb. If the block lies on its side, how much work does a man do in standing the block on end?

7. If the coefficient of friction is 0.15, how much work does a man do if he pulls a sled weighing 200 lb. a distance of 1000 ft.? What horse power does he use if he does the work in 4 minutes?

8. How many tons of ore can be lifted from a mine 900 ft. deep by an 80-horse-power engine working 24 hours?

9. A locomotive develops 500 horse power. If it pulls a train at the rate of 60 miles per hour, what effort does it use to keep the train in motion?

10. A man who weighs 160 lb. climbs a ladder 16 ft. high with a hod of brick weighing 70 lb. How much work does he do? How much of this work is really worth while?

11. Man power is about 4600 ft. lb. per minute. How many trips up the ladder should the man in Problem 10 make in one hour to be working at average man power?

12. An automobile weighing 3500 lb. climbs a hill 600 ft. high in 1.5 minutes. What is the minimum horse power engine needed?

C. ENERGY

179. Energy Defined. *Energy is the capacity for doing work.* An inorganic body has energy, if work has been done in lifting it to some elevated position or in imparting to it velocity. Flowing water has energy because the pull of gravity has given it velocity. Wind is a similar example. Steam has expansive force; hence it is able to exert pressure and do work. A weight lifted to an elevated position has had work done upon it; it has energy of position. Heat, light, electricity, and mechanical energy are some of the types of energy with which physics deals.

180. Kinds of Energy. Energy is of two kinds, *kinetic* and *potential. Kinetic energy is energy of motion;* a body has kinetic energy due to its velocity. A moving cannon ball, strong winds, falling and running water are all examples of kinetic energy. *Potential energy is stored energy, or energy of position.* A rock resting on a precipice has potential energy; if it falls over the edge, its energy becomes kinetic. A coiled spring has potential energy. Work was done in winding the spring; as it unwinds, its energy becomes kinetic. Gasoline has potential energy. When a mixture of gasoline vapor and air explodes, it is capable of doing work. Potential energy may be transformed into kinetic, or vice versa.

181. Measurement of Energy. Since energy is the capacity for doing work, one would expect that the work units would also be used for measuring energy. For example, we do 120 ft. lb. of work in lifting a weight of 40 lb. to a table

3 ft. high. The weight in its elevated position has acquired 120 ft. lb. of potential energy. In falling a distance of 3 ft., this stored energy could do 120 ft. lb. of work. (See Fig. 220.)

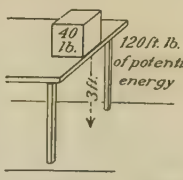


Fig. 220. — Potential energy equals weight times height.

Potential energy equals mh, or mass times height. If the mass is expressed in grams and the height or distance in centimeters, then the potential energy will be expressed in gram centimeters. If the mass is expressed in pounds and the distance in feet, the potential energy will be expressed in foot pounds. To find potential energy in ergs or foot poundals, we use the formula: P.E. (in ergs or foot poundals) $= mgh$. Of course g is the acceleration due to gravity, 980 cm. per sec., or 32.16 ft. per sec.

If the velocity of the body is given, its kinetic energy may be found by the use of the following formula:

$$\text{K.E. (in ergs)} = \tfrac{1}{2}\, mv^2.$$

The above formula is derived from the formulas mgh and $v = \sqrt{2gS}$. S and h both represent distance. From $v = \sqrt{2gS}$, we get $S = \dfrac{v^2}{2g}$.

Substituting, $\text{K.E.} = mg \times \dfrac{v^2}{2g}$. Or, K.E. $\tfrac{1}{2}\, mv^2$.

Problem. A bullet having a mass of 50 gm. moves with a velocity of 1000 meters per second. Find its kinetic energy in ergs and in gram centimeters. In kilogram meters.

Solution. Substituting in the formula, K.E. $= \tfrac{1}{2}\, mv^2$, we have the following: K.E. $= 25 \times (100{,}000)^2$, or 250,000,000,000 ergs. Dividing the number of ergs by 980, we have 25,510,201 gm. cm. There are 100,000 gm. cm. in 1 Kgm. m. Hence 25,510,201 gm. cm. = 255 Kgm. m.

In the English system,

K.E. (in foot poundals) $= \frac{1}{2} mv^2$, when m is expressed in pounds and v in feet per second. Dividing by 32.16 gives the K.E. in foot pounds.

182. Conservation of Energy. Like matter itself, energy can neither be created nor destroyed. There is the same amount of energy in the universe today that there was yesterday, and the amount will be unchanged tomorrow. These facts show why the *output* of a machine can never exceed the *input.* A perpetual motion machine is utterly impossible. Even if friction and the weight of the parts could be eliminated, the machine could never create energy; it would never have any more energy than was put into it.

183. Transformations of Energy. Although energy cannot be created, it can be transformed from one kind into another. We have already learned that it is possible to transform kinetic energy into potential energy, and vice versa. Heat energy can be transformed into mechanical energy, mechanical into electrical, and electrical into mechanical, heat, or light energy. Let us use just one concrete example. Heat from the sun evaporates water; some of this vapor, which is carried by winds may fall as rain into Lake Erie. Here its potential energy is transformed into kinetic as the water flows down Niagara River to the Falls. This transformation continues as it passes through the turbine pits and turns the large wheels at the bottom, thus producing mechanical energy. The turbines turn alternators which generate electricity. This electrical energy is transmitted to various places, where it is utilized for lighting, heating, or in the mechanical work of turning motors. In these cases heat energy is set free, either in doing useful work or in overcoming friction. This heat may evaporate more water to begin anew the energy transformations. During all these transformations the total amount of energy is unchanged. The fact that energy may be transformed or transferred,

but cannot be destroyed, is known as the *law of the conservation of energy.* Fig. 221 shows the dam built across the

FIG. 221. — The dam across the Mississippi River at Keokuk, Iowa. The power house is shown at the left.

Mississippi River at Keokuk, Iowa. The kinetic energy of the "Father of Waters" is transformed into about 180,000 horse power of electrical energy.

SUMMARY

When a force acts upon a body and produces motion, work is done upon that body. The gm. cm., Kgm. m., and ft. lb. are gravitational units of work. The erg, the joule, and the foot poundal are absolute units of work. One foot pound equals 32.16 foot poundals. One gram centimeter equals 980 ergs.

Power is the rate of doing work. The horse power, watt, and kilowatt are the units of power. The horse power equals 550 ft. lb. per second.

Energy is the capacity for doing work. The units of work are used to measure energy. Energy can neither be created nor destroyed. It may be transformed in practically any manner.

In dealing with force, we consider magnitude only; with work, we consider both magnitude and distance; with power, we consider magnitude, distance, and time.

PROBLEMS

1. Find the potential energy of 1 cu. ft. of water at the top of Niagara Falls. (Height equals 164 ft.)

2. A projectile weighing 1000 lb. moves with a velocity of 2500 ft. per sec. Find its kinetic energy in foot poundals; in foot pounds; in foot tons.

3. If all the kinetic energy of problem 2 were transformed into work, to what height could the projectile be lifted? (Divide kinetic energy in ft. lb. by the weight of the projectile.)

4. Using the formula, $v = \sqrt{2gS}$, find out how high a body projected upward with a velocity of 2500 ft. per sec. would rise. Compare the result you obtain with the answer to problem 3.

5. A waterfall is 140 ft. high. If 1000 cu. ft. of water flow over it per second, what horse power can it develop?

6. An automobile weighing 3000 lb. climbs at the rate of 30 mi. per hr., a hill that rises 8 ft. in 44 ft. of its length. What is the minimum horse power developed by the engine?

7. A pile-driver weighs 1000 lb. In falling 4 ft. how far will it drive a pile if the earth resistance is 6000 lb.?

8. An automobile weighs 3500 lb. and is moving with a velocity of 45 miles per hour. What is its momentum?

9. Calculate the kinetic energy of the automobile of problem 8, first in foot poundals and then in foot pounds.

10. How many cubic feet of water must pass over a waterfall 220 ft. high each second in order to develop 120,000 horse power?

CHAPTER 8

MACHINES

A. DEFINITIONS—PRINCIPLES

Vocabulary

Machine, a device to transfer or transform energy.
Mechanical advantage, the advantage of force or speed gained by the use of a machine.
Efficiency, the ratio of the useful work accomplished to the total work expended.
Penstock, a tube or conduit for conducting water to a turbine.
Cam, a projection on one side of a rotating wheel designed to impart motion to a roller in contact with the edge of the wheel.
Reciprocating, backward and forward, or to and fro, as distinguished from rotary.

184. Machines. Without the use of machines, man could hardly have been able to combat the tremendous forces of nature and the ferocious wild beasts of our forests. The Greek philosopher, Archimedes, said he could lift the earth if he were given a long enough lever and some spot to put the fulcrum. Man uses machines to *transform* or to *transfer* energy. The dynamo changes mechanical energy into electrical energy. The steam engine transforms heat energy into mechanical energy. Then energy of flowing water is transformed into electrical energy by hydroelectric machines. Quite as often it is desirable to apply energy at one place and have it *transferred* by a machine to some other place.

We use machines to *multiply force,* to *increase speed,* or to *change the direction in which a force is applied.* A nail that cannot be pulled with the fingers may be drawn with a

claw hammer used as a lever. By means of a jack-screw the axle of an automobile is lifted so that the wheel or tire can be removed. Two men wish to hoist a piano to the second floor of a house. If either one were strong enough, he might carry it upstairs. Instead they arrange a system of pulleys by means of which the piano can be hoisted without so much effort. In all of these machines, *the effort used has been multiplied by the use of the machine,* but *the time needed has been increased. We have gained effort at the sacrifice of time.*

A bicycle is a machine used to gain speed. In this case we increase speed by increasing our effort. The increased effort becomes evident when we try to ride a bicycle up a steep hill. It is impossible to gain both force and speed at the same time. To put up a flag on a tall pole, one *could* climb the pole and carry the flag with him. It is much more convenient, however, to have a pulley at the top of the pole, and a rope twice as long as the pole. Then one may stand on the ground and pull the flag up by means of the rope. He must pull down with a force of 1 lb. for every pound the flag weighs; hence the single fixed pulley as a machine does not multiply force. He must also shorten the rope 1 ft. for every foot the flag is raised; hence no speed is gained. As he pulls downward the flag moves upward. This machine is used only *to change direction.* The farmer who wishes to use horses to lift hay to a mow would have difficulty in getting his horses into the mow to pull upward or to hitch the horses so they could pull downward. By two or three fixed pulleys fastened to the rafters and the posts by the side of the barn door, the horses may pull horizontally and the hay move upward.

185. Simple Machines. Six simple machines are usually discussed in physics: the *lever;* the *pulley;* the *wheel and axle;* the *inclined plane;* the *screw;* and the *wedge.* Other machines are either modifications of one of these simple machines,

or combinations of two or more of them. It is also quite easy to show that the pulley and the wheel and axle are really levers, and that the wedge and the screw are inclined planes.

186. Mechanical Advantage. In § 38 we learned that a machine has a mechanical advantage of 5, if by its use 1 lb. of effort can counterbalance 5 lb. of resistance. In all the simple machines we shall use the term *mechanical advantage* frequently. There are two ways in which this mechanical advantage can be found. 1. By the use of a spring balance the *acting force, E,* can be measured and also the *resisting force, R.* Then the mechanical advantage equals $\frac{R}{E}$. 2. With a ruler we may measure the *distance the effort* moves, *De,* and also the *distance the resistance moves, Dr.* In this case, the mechanical advantage equals $\frac{De}{Dr}$. In dealing with mechanical advantage we always assume that the parts of the machine have no weight and that there is no friction. Of course such an assumption is theoretical; it tells us what a machine *should* do under *ideal* conditions.

187. General Law of Machines. In the preceding section, we had two statements for mechanical advantage. Both are equal to each other. Then,

$$\frac{R}{E}=\frac{De}{Dr}. \quad \text{Or, } E\times De=R\times Dr.$$

In all frictionless machines, *the effort multiplied by the distance the effort moves equals the resistance multiplied by the distance the resistance moves.* This statement is known as the *Law of Machines.*

The effort times the distance it moves equals the *work* put into the machine, or *input.* The resistance times the

distance it moves equals the work accomplished by the machine, or its *output*. If we *neglect friction and weight of parts, input equals output.*

188. Efficiency. When a man rides a bicycle up a hill, he must lift his own weight and also that of the bicycle the vertical height of the hill. Lifting the bicycle is really *useless work.* No machine ever runs without some friction. Overcoming friction wastes work. Hence input is always greater than output. In practice, we are more interested in what a machine *actually does* than in what it *should do theoretically.* We are concerned with the useful work that is accomplished. *The efficiency of a machine is the ratio of the useful work accomplished to the total work expended.* Or,

$$\text{Efficiency} = \frac{\text{useful work}}{\text{total work}}.$$

When efficiency is considered, *input equals useful work plus friction.* Efficiency is usually expressed in per cent. If a pupil solves 8 problems out of 10 correctly, his efficiency is 80%. If a machine has a total input of 1000 ft. lb., and its useful output is only 800 ft. lb., the machine is working at an efficiency of 80%.

Suppose an effort of 40 lb. moves 20 ft. along an inclined plane and in so doing lifts a weight of 180 lb. to a height of 4 ft. The *useful* work done equals 4×180, or 720 ft. lb. The *total* work equals 40×20, or 800 ft. lb. Then the efficiency equals $\frac{720}{800}$; dividing, we get a quotient of 0.90, or 90%.

If we have a machine which has a mechanical advantage of 5, a force of 20 lb. should support a weight of 100 lb. If actual experiment shows that it takes 25 lb. to support 100 lb., then the efficiency of the machine is $\frac{20}{25}$, or 80%. The

additional 5 lb. of force required to counterpoise the weight of the machine itself represents wasted effort.

B. LEVER

189. The Lever. When a man rows a boat, he uses the oars as levers. We see a man using a crow-bar to lift a heavy load. He is using the same kind of a lever Archimedes would have used to lift the earth. The can opener, the broom, and the shovel are levers used around the house. The lever consists of a rigid bar free to turn about a fixed point called the *fulcrum*. The fulcrum is essentially the center of moments, and the effort and resistance act upon the arms of the lever as they tend to produce rotation in opposite directions. In using the lever, we make use of the principle of moments.

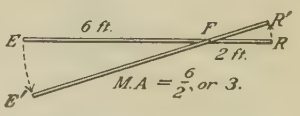


FIG. 222. — Mechanical advantage of the lever.

190. Mechanical Advantage of the Lever. In Fig. 222 we shall use the letter F to represent the fulcrum of the lever ER.

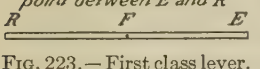


FIG. 223. — First class lever.

At E the effort acts upon the arm EF as it tends to produce *counter-clockwise* rotation. The resistance R acts upon the arm RF as it tends to produce *clockwise* rotation. If the effort moves from the point E to E', the resistance will move from R to R'. But the distance $EE' : RR' = EF : RF$. Hence it follows that the distances moved by the effort and resistance are proportional to the lengths of the arms upon which they act. In all frictionless machines, $\text{M.A.} = \frac{De}{Dr}$. In all kinds of levers, $\text{M.A.} = \frac{EF}{RF}$. If EF is 6 ft. long, and RF is only 2 ft. long, then the mechanical advantage is 3.

191. Classes of Levers. 1. With a lever it is possible to have the effort act at or near one end. The resistance is placed

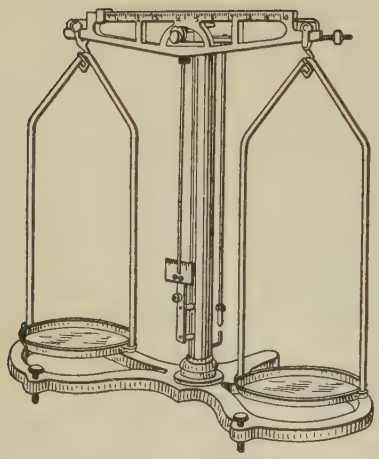


Fig. 224. — Beam balance.

at the opposite end of the lever, and the fulcrum is between the two. (See Fig. 223.) Such a lever is known as a *first-class* lever. Such a lever may be used to gain speed, to gain force, or to change direction. The beam balance, Fig. 224, is a common example of a lever of this class. If such a balance is well constructed, the two arms are of equal length and the light, rigid beam rests upon a very hard, knife-edged fulcrum. Accurate weighings can be made with such a balance. If *EF* exceeds *RF* in length, we have a mechanical *advantage of force*. The pump-handle of Fig. 97 is a common example. The mechanical advantage is more than *one*, because the effort arm exceeds in length the resistance arm. The tinner's shears of Fig. 225 furnish another example. Sometimes a first-class lever is used to gain speed. Then the effort arm is shorter than the resistance arm. The force advantage is a fraction in such cases. Paper shears, or those used by a tailor, are examples. (See Fig. 226.)

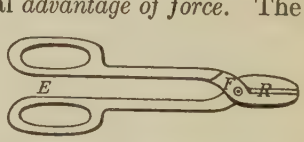


Fig. 225. — Tinner's shears.

Fig. 226. — Paper shears.

2. Sometimes the effort is applied at one end of a lever and the fulcrum is at the other end. The resistance is placed between the effort and the fulcrum. (See Fig. 227.) Such a lever is known as a *second-class* lever. In a wheelbarrow, the

axle of the wheel is the fulcrum. The effort is applied at the ends of the handles, and the load or resistance is between the two. (See Fig. 228.) Since the effort arm of a second-class lever is the *whole* lever, and the resistance arm is only a *part* of the lever, *EF* is always greater than *RF*. The mechanical advantage of such a lever is always *more than one*. The nut-cracker and the baggage-truck are other examples of this class of lever.

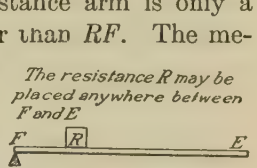


Fig. 227. — Second-class lever.

If two boys carry a load on a pole between them, we may consider the pole a second-class lever, and one of the boys the fulcrum. Then it is easy to find the force the second boy must use to lift the load.

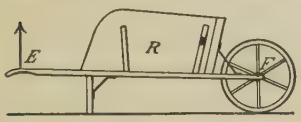


Fig. 228. — A second-class lever.

3. When we lift a weight on the hand, we use the forearm as a *third-class* lever. The fulcrum is at the elbow. The resistance is at the other end of the lever, on the hand, and the tendons attached to the bones of the forearm act as the effort. (See Fig. 229.) This lever differs from the second-class lever in one way only. The positions of the effort and resistance have been interchanged. (See Fig. 230.) The resistance arm is longer than the effort arm; hence the resistance must move faster than the effort. Such a lever is used to gain speed. Of course we gain speed by sacrificing force. A fork, a shovel, or a broom may be used as a third-class lever; sometimes they are used as first-class levers. We find it very hard to open a door by pushing near the hinge. The resistance is *concentrated at the center of gravity* of the door, and we have been using

Fig. 229. — This lever is used to gain speed.

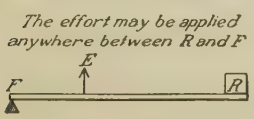


Fig. 230. — Third-class lever.

a third-class lever. The door opens much more easily when we push near the other edge of the door, but the hand must move farther.

192. How a Lever Is Affected by Its Own Weight. In the preceding section, we neglected the weight of the lever. In practice the weight of the lever must be considered. We must keep in mind that the lever *acts as if all its weight were concentrated at its center of gravity.*

In Fig. 231, the uniform bar AB is 12 ft. long; its weight is 60 lb. At B, 2 ft. from the fulcrum F, there is a resistance of 300 lb. We wish to find what effort at A is needed to produce equilibrium. The resistance moment equals 2×300, or 600. It acts clockwise. The effort moment equals $10\times x$, or $10x$; its direction is counter-clockwise. But the weight of the lever, 60 lb., acting at its center of gravity, 4 ft. from the fulcrum, is really producing a counter-clockwise moment and helping the effort. The sum of the two counter-clockwise moments is $10x+(4\times60)$. This sum equals the clockwise moment, 600. From the equation, $10x+240=600$, we find that $x=36$ lb., the effort needed at A.

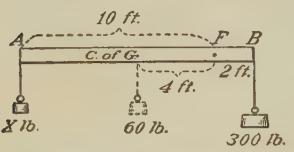


FIG. 231. — Weight of lever acts as a counter-clockwise moment.

In Fig. 232 the weight of the lever hinders the effort, since it acts in a counter-clockwise direction, the same as the resistance. The lever EF has the fulcrum at the end F, and the effort is applied at the other end E. The lever, which is 12 ft. long, weighs 60 lb. A resistance of 300 lb. is applied at R, 2 ft. from the fulcrum. We wish to find the effort needed at E to secure equilibrium. The resistance moment, 2×300, or 600, and the weight moment, 6×60, or

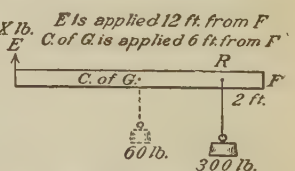


FIG. 232. — Weight of lever hinders the effort.

360, are both acting in a counter-clockwise direction. Their sum is 960. The effort moment, $12 \times x$, or $12x$, acts clockwise. Therefore $12x = 960$, and $x = 80$ lb., the effort needed at E. *A lever acts as if all its weight were concentrated at its center of gravity; its weight moment equals its weight multiplied by the distance from the center of gravity to the fulcrum.*

QUESTIONS

1. Determine the position of the effort, fulcrum, and resistance in each of the following levers: a claw hammer used for pulling nails, Fig. 233; a pair of sugar tongs; a nut-cracker; the oar of a rowboat; the lower jawbone.

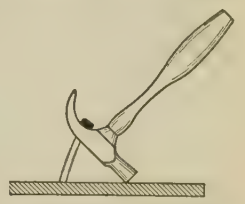


FIG. 233. — Hammer, a bent lever.

2. Where should the resistance be placed to secure a high mechanical advantage with a second-class lever?

3. Where must the effort be placed with a third-class lever to secure a high mechanical advantage of speed?

4. In what class of lever is the weight of the lever usually a help? In what class is it a hindrance?

PROBLEMS

1. If a boy can exert a force of 100 lb., how heavy a load can he lift with a second-class lever, 12 ft. long, if the resistance is placed 3 ft. from the fulcrum?

2. If the lever of the preceding problem is used as a first-class lever, how heavy a load can the boy lift?

3. A boy weighing 60 lb. sits on one end of a see-saw, 5 ft. from the fulcrum. How far from the fulcrum must a 70-lb. boy sit to secure equilibrium?

4. A bar 6 ft. long is to be used to lift a weight of 600 lb. The maximum effort that can be used is 75 lb. If the bar is used as a second-class lever, how far from the fulcrum must the resistance be placed?

5. A bar 5 ft. long is to be used as a first-class lever. If 60 lb. of effort at one end are needed to balance a resistance of 240 lb. at

the other end, where must the fulcrum be placed? (Hint: Let x equal the length of one arm, and $5-x$ the length of the other arm.)

6. A plank 16 feet long weighs 100 lb. It lies on a flat roof with exactly 2 feet of its length projecting beyond the edge of the roof. How heavy a weight can be hung from this end without pulling the plank off the roof?

7. A uniform bar 4 ft. long weighs 16 lb. When a certain weight is applied at the end A, the combination balances on the fulcrum F, which is 1 ft. from A. Find the value of the weight.

8. The weight of a uniform bar 30 ft. long is 600 lb. The fulcrum is at F, 5 ft. from the end A, from which a weight of 2000 lb. is suspended. What effort applied at the other end is needed to secure equilibrium?

9. A meter stick loaded at one end balances on a fulcrum placed 20 cm. from the loaded end. A weight of 500 gm. is attached to the other end, and it is then found to balance on a fulcrum placed 35 cm. from the weight. Find the weight of the loaded meter stick.

10. A pole 50 ft. long has its center of gravity 15 ft. from one end. A weight of 2000 lb. is suspended from this end. If the pole weighs 1000 lb., what effort at the other end will balance the pole on a fulcrum placed midway between the ends?

11. A uniform bar, 24 ft. long, weighs 1000 lb. The fulcrum is 6 ft. from the end A, from which a weight of 500 lb. is suspended. What effort at the other end is needed to produce equilibrium, and in what direction must it act?

12. A pole AB is 40 ft. long. It weighs 400 lb., and its center of gravity is 15 ft. from the end A, which is 10 ft. from the fulcrum. A weight of 1500 lb. is attached at A, and a weight of 200 lb. is suspended at a point 5 ft. from B. Where must a weight of 400 lb. be applied to produce equilibrium?

C. THE PULLEY

193. The Pulley finds extensive use. The cords that support our windows pass over fixed pulleys. We see men in the country putting hay in the mow by means of ropes and pulleys. The painter uses pulleys to raise or lower his ladders, and the man who moves household goods finds frequent use for a block and tackle, which is a system of pulleys.

The *pulley* consists of a wheel, usually grooved, so mounted in a frame or block that it may turn readily upon a fixed axis. The frame may be made of metal or of wood. When two wheels are mounted in the same block, the pulley is said to have two *sheaves*. When a pulley has two or more sheaves, they generally are mounted on a common axis. (See Fig. 234.) Sometimes they are mounted on different axes, as in Fig. 235. For the sake of clearness, we shall use pulleys of the latter type in diagrams, although the first type is more common in practice.

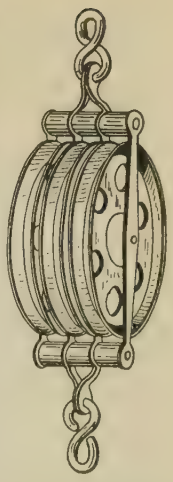


FIG. 234. — Pulley, three sheaves. All on same axle.

FIG. 235. — Pulley, three sheaves.

194. Single Fixed Pulley. A single fixed pulley is really a lever of the first class. The arms *EF* and *RF*, Fig. 236, are equal; hence the mechanical advantage is one. When 1 lb. pulls downward at *A* through a distance of 1 ft., a resistance of 1 lb. at *B* is raised 1 ft. A single fixed pulley gains neither force nor speed; its purpose is to change the direction in which a force is applied.

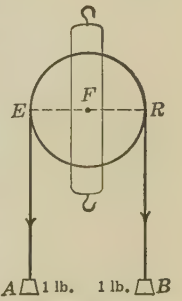


FIG. 236. — Single fixed pulley.

195. Single Movable Pulley. The single movable pulley is really a lever of the second class. In Fig. 237, the effort *E* acts upon the arm *EF*, which is the diameter of the pulley. The resistance *R* acts upon the arm *RF*, which is the radius of the pulley. Since the diameter is twice the radius, the mechanical advantage of the single movable pulley is two. When the effort

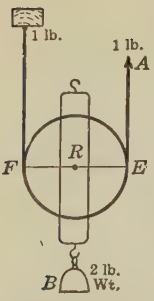


FIG. 237. — Single movable pulley.

at A moves 2 ft., the resistance at B is lifted 1 ft. If we fasten both ends of the cord, it is evident that each point of support bears one half the weight.

196. Combinations of Pulleys. Many combinations of fixed and movable pulleys are in use. In Fig. 238, one end of the continuous cord or rope is attached to a hook in the *movable* block; the effort is applied at the other end of the rope. The effort E must pull downward through a distance of 5 ft. to raise the resistance R one ft. There are 5 divisions or strands of cord supporting the movable block. If we use the letter n to represent the number of strands of cord supporting the movable block in any combination of fixed and movable pulleys where the cord is continuous, then $En = R$. *The mechanical advantage equals the number of strands supporting the movable block.* The strand of cord to which the effort is attached does not support the movable block. It merely changes direction, and it does not increase the mechanical advantage.

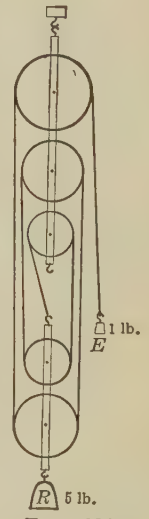


FIG. 238. — Five strands support the movable block.

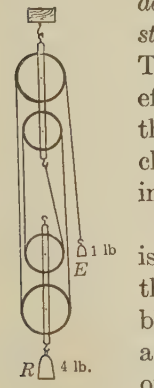


FIG. 239. — Four strands support the movable block.

In Fig. 239 one end of the cord is attached to the *fixed* block and there are four strands supporting the movable block. The mechanical advantage of such a system of pulleys is four. The last strand over the fixed pulley, which merely changes direction, must not be counted. When one end of the cord is attached to the fixed block, the mechanical advantage is always an *even* number.

When one end of the cord is attached to the *movable* block, the mechanical advantage is always an *odd* number.

D. WHEEL AND AXLE

197. The Wheel and Axle. It is quite probable that at some time you tried to open a door and found that the door knob had been removed. When you found it difficult to turn the bolt without the knob, you appreciated the advantage gained by the use of one of the most common types of wheel and axle. The effort is applied to the circumference of the knob, and the resisting spring is applied to the circumference of the axle. Since the circumference of the knob is much greater than that of the axle, a mechanical advantage of force is gained, because *De* is greater than *Dr*.

A wheel turning on an axle, the front wheel of a car, for example, is *not* an application of this machine. In the rear wheel of an automobile, the wheel is fastened to the axle and turns with it. It *is* an application. The *wheel and axle* as a simple machine consists of a wheel or crank rigidly attached to an axle so that both are free to turn about a common center.

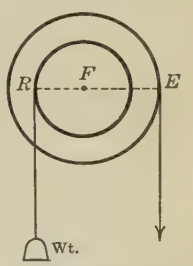


FIG. 240. — Wheel and axle.

In Fig. 240 we have two wheels of unequal diameter turning about the center at *F*. The effort is applied at *E*, and it travels the entire circumference of the wheel, *C*, in one revolution. The resistance is applied at *R*, and it travels the entire circumference of the axle, *c*, in one revolution. Hence *De* equals *C*, and *Dr* equals *c*. Since $\frac{De}{Dr} = \text{M.A.}$ for any machine, then $\frac{C}{c} = \text{M.A.}$ for this especial machine. Instead of the expression,

$$\text{M.A.} = \frac{\text{circumference of wheel}}{\text{circumference of axle}}$$

we may use either of the following expressions:

$$\text{M.A.} = \frac{\text{diameter of wheel}}{\text{diameter of axle}}, \quad \text{or} \quad \text{M.A.} = \frac{\text{radius of wheel}}{\text{radius of axle}}.$$

The reason is obvious, for the circumferences of the two wheels are directly proportional to their diameters or to their radii.

PROBLEM. A force of 100 lb. is applied to the rim of a wheel 2 ft. in diameter. What resistance can be counterbalanced upon the axle, which has a diameter of 4 inches?

Solution. The M.A. of this wheel and axle equals

$$\frac{\text{diameter of wheel (24 in.)}}{\text{diameter of axle (4 in.)}}.$$

Since the machine has a mechanical advantage of 6, then 100 lb. of force can counterbalance a resistance of 600 lb.

198. Applications of the Wheel and Axle. The *capstan* used for hoisting the anchor of a ship is an example of the wheel and axle in which the effort is applied at the ends of several levers. (See Fig. 241.) The *windlass* used for lifting water from wells is another example of the wheel and axle. As the crank of Fig. 242 is turned, the rope is wound upon the axle, thus lifting the bucket and contents. The *hoisting derrick* works on the same principle, and also the *steering wheel* on motor boats.

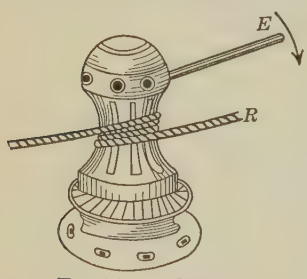


FIG. 241. — Capstan.

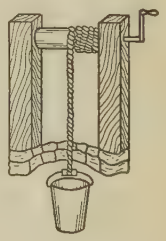


FIG. 242. — Windlass.

E. INCLINED PLANE

199. The Inclined Plane. We see men wheeling loads up an inclined gang-plank, pushing weights up inclined planks to load motor trucks, and building ramps for the use of spectators at athletic contests, or for driving automobiles to the upper floors of garages for parking. In all these cases it is much easier to pull or push the resistance up the inclined surface than it is to lift it vertically. (See Fig. 243.) The effort travels the length of the plane in lifting an object a distance equal to the height of the plane, if the *force is applied parallel to the plane.* Since *De* is the length of the plane, and *Dr* is the height of the plane, then

FIG. 243. — Inclined plane.

$$\text{M.A.} = \frac{\text{length of plane}}{\text{height of plane}}. \qquad \text{Or, M.A.} = \frac{l}{h}.$$

Theoretically, 1 lb. of effort will pull or push a weight of 5 lb. up an inclined plane 20 ft. long and 4 ft. high.

Effort : resistance = height : length.

A team of horses pulling a log up inclined skids to a wagon, walks along the ground, and their pull is *parallel to the base of the plane.* In this case, the $\text{M.A.} = \frac{\text{base of plane}}{\text{height of plane}}$.

In other cases, it may be inconvenient to apply the effort parallel to the plane; then it is applied either parallel to the base, or at some other angle.

200. Grade. We know that the advantage of the inclined plane becomes greater as the slope is made more gentle. Engineers use the term "grade" to express the ratio of the height of an incline to its length. A hill that rises 5 ft. in 100 ft. of its length has a grade of 5%; if it rises 3 ft. in 100 ft. of its length, its grade is 3%. This is about the maximum grade for a good road; hence in mountain regions the roads often wind about the mountain in a long spiral in order to

reduce the grade. (See Fig. 244.) A zigzag path, or switchback, is sometimes used by trolley lines. At one point in the Appalachian Mountains, known as Horseshoe Curve,

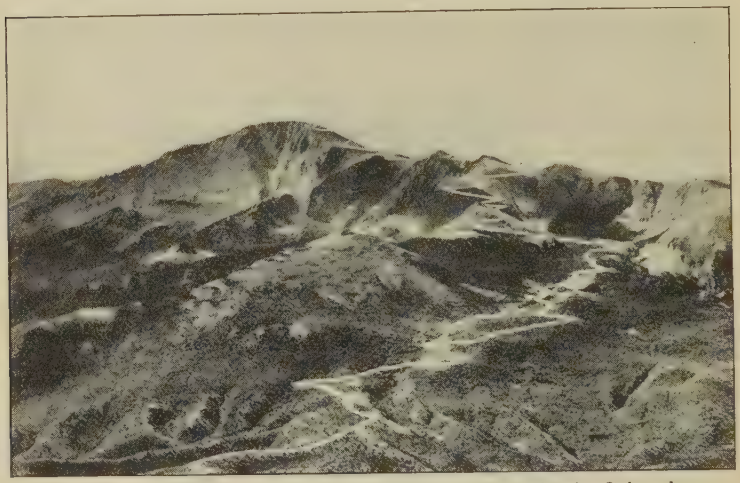


FIG. 244. — Winding road up to the top of Pike's Peak, Colorado.

the Pennsylvania Railroad makes a loop, as it winds its way to a higher level.

PROBLEM. An inclined plane is 18 ft. long and 2 ft. high. What force will be needed to keep a weight of 2000 lb. from sliding down the plane, if we neglect friction?

Solution. $E : R = h : l$. By substitution, $E : 2000 = 2 : 18$. Whence, $E = 222.2$ lb. Or, by analysis, we find that the M.A. $= \frac{l}{h}$, or 9. When one has a mechanical advantage of 9, it will require $\frac{2000}{9}$, or 222.2 lb. to counterbalance 2000 lb.

F. THE WEDGE

201. The Wedge. The wedge is really a double inclined plane. Since friction plays so important a part in its use,

it is difficult to state any accurate law governing its mechanical advantage. Of course the longer the wedge in proportion to its thickness, the easier it is to drive the wedge against any resistance; hence its mechanical advantage depends upon the ratio of its length to its thickness. (See Fig. 245.)

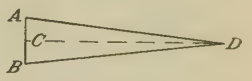


FIG. 245. — Wedge is a double inclined plane.

The uses to which the wedge is put vary widely. Farmers use the wedge for splitting rails and posts. Nails, pins, and needles all act as wedges when they are pushed or driven through some resisting object. Cutting tools of nearly all kinds are wedges.

QUESTIONS

1. What type of machine is a brace and bit, used for boring a hole in a plank?

2. Is it easier to bore a hole with a 1-in. bit, or with one that is $1\frac{1}{2}$ in. in diameter? Explain.

3. How heavy a load can a man lift with a single fixed pulley?

4. From a consideration of Fig. 240, show that a wheel and axle is really a lever.

5. Make a list of at least six applications of the wheel and axle as used around the home.

6. What type of machine is a screw driver?

PROBLEMS

1. Draw a diagram of a system of fixed and movable pulleys so arranged that 1 lb. of effort will counterpoise 6 lb. of resistance.

2. Diagram a block and tackle by which 50 lb. will counterbalance 200 lb.

3. Two men operate a windlass. If the wheel has a diameter of 4 ft. and the axle a diameter of 8 in., how much force must each use to overcome a resistance of 2000 lb.?

4. The steering wheel of an automobile is 18 in. in diameter and the shaft to which it is attached is $1\frac{1}{2}$ in. in diameter. A force of 10 lb. is applied to the wheel. How much resistance on the shaft can this force overcome?

5. The handle of a screw driver is $1\frac{1}{4}$ in. in diameter and the blade is $\frac{3}{8}$ in. wide. What mechanical advantage is gained by the use of the screw driver?

6. In a system of pulleys the effort moves 7 ft. in moving the resistance 1 ft. If 60 lb. are required to lift a load of 300 lb., what is the efficiency of the system?

7. A boy can exert a force of 60 lb. How long a plank must he use to roll a barrel weighing 200 lb. up into a wagon 3 ft. high?

8. A man uses a plank 16 ft. long to roll a barrel weighing 300 lb. to a floor 4 ft. high. If the plank weighs 100 lb., how much work does he do in putting the plank into position? Neglecting friction, what force must he use to push the barrel up the plane?

9. If a man does 1350 ft. lb. of work in rolling the barrel up the plane as described in problem 8, what is the efficiency of the plane?

10. How much force must a horse exert to pull a wagon weighing 1000 lb. up a 3% grade?

11. A 50-horse-power engine in 40 min. hoists 60 tons of coal of 2000 lb. each from a mine 440 ft. deep. What is its efficiency?

12. What horse-power engine will be required to lift a weight of 8000 lb. to a height of 110 ft. in 6 minutes, if it works at an efficiency of 100%?

13. What horse-power engine will be required to do the work specified in problem 12 in 6 minutes, if the engine has an efficiency of only 80%?

14. A man who weighs 150 lb. carries a bag of sugar weighing 100 lb. to the third floor of his house, a total height of 20 ft. How many foot pounds of work does he do? How much useful work does he do? What is his efficiency? How could he arrange a simple machine to do work of this kind at greater efficiency?

G. THE SCREW

202. The Screw. If we examine Fig. 246, we see that the screw is merely an inclined plane wound upon a cylinder or axis. The distance between the threads is known as the *interval* or *pitch* of the screw. The effort is generally applied at one end of a lever, the other end being inserted in the head of the screw. (See Fig. 247.) While the effort describes

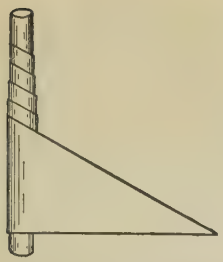


FIG. 246. — The screw is an inclined plane wound on a cylinder.

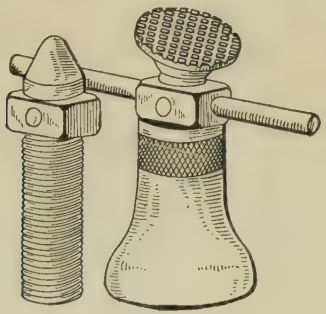


FIG. 247. — Screw.

a complete circle, the screw makes one complete turn, and the resistance moves a distance equal to the pitch of the screw. Then

$$\text{M.A.} = \frac{\text{circumference described by effort}}{\text{pitch}}.$$

Let r equal the length of the lever, and d the pitch of the screw. Then the

$$\text{M.A.} = \frac{2\pi r}{d}.$$

PROBLEM. The lever of a screw is 21 in. long. If the screw has 4 threads to the inch, find the M.A. of the machine. Neglecting friction, what effort is needed to lift 40,000 lb.?

Solution. $\text{M.A.} = \frac{2\pi r}{d}$, or $\frac{2 \times \frac{22}{7} \times 21}{0.25}$. (Since there are 4 threads to the inch, the pitch is 0.25 in.) M.A. = 528. To lift 40,000 lb., an effort of $\frac{40{,}000}{528}$, or 75.75 lb., is needed.

203. Uses of the Screw. Bolts, nuts, and screws of all kinds are examples of this simple machine. When the threads on a bolt are cut so that the nut must be turned in a clockwise direction as it is tightened, the screw is said to be a right-handed one. When the nut must be turned in a counter-

clockwise direction to tighten it, the screw or thread is said to be left-handed. (See Fig. 248.) The *letter press* and the *vise* are examples of the screw. The *jack-screw* which is used for lifting buildings and other heavy objects is a screw having a very high mechanical advantage. For measuring the thickness of paper and foil, or for finding the diameter of wire, a fine-threaded screw may be used. Fig. 249 shows the *spherometer*. The head of the screw is divided into 50 or 100 parts. If the threads are 1 mm. apart and the head is divided into 100 parts, it is evident

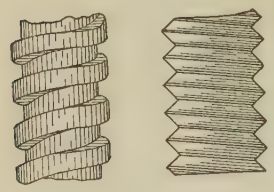


Fig. 248. — Right and left-handed screws. Square and V-threads.

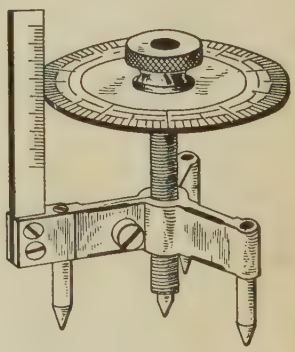


Fig. 249. — Spherometer.

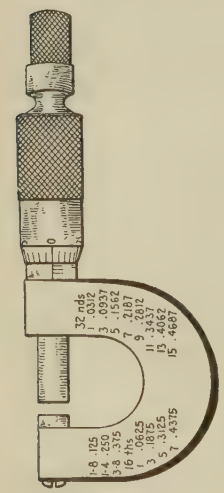


Fig. 250. — Micrometer.

that the point of the screw moves only 0.01 mm. when the head is turned from one division to the adjacent one. The *micrometer caliper* of Fig. 250 is used in the same manner. By the use of such a caliper a skilled mechanic can turn a shaft in a lathe to a required diameter within a few thousandths of an inch.

H. COMPOUND MACHINES

204. Compound Machines. Many machines are more complicated than the simple machines just discussed. A detailed study of such machines shows that they are usually made up of two or more simple machines acting upon each other. In such cases the mechanical advantage is equal to the product of the advantages of the several simple machines.

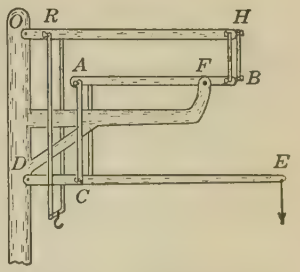


FIG. 251. — Compound lever.

Fig. 251 shows a compound lever. The effort E acts upon the second-class lever ED. If ED is 40 in. long and CD 8 in., its M.A. is 5. Then 1 lb. at E exerts a downward pull of 5 lb. at C. But C acts downward upon A, one end of the first-class lever AB. Suppose AF is 20 in. long and BF 4 in.; this lever has a mechanical advantage of 5, and the 5 lb. force, acting at A, will exert an upward force of 25 lb. at B. This force of 25 lb. acts on H, one end of the second-class lever OH, of which the arm HO is 28 in. long and OR is 4 in. Such a lever has a mechanical advantage of 7. Therefore, 25 lb. at H will just counterbalance a weight of 175 lb. applied at R. The total advantage of such a system of levers *equals the product (not the sum) of all the separate mechanical advantages.* For example, $5 \times 5 \times 7 = 175$.

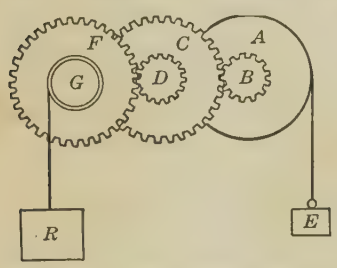


FIG. 252. — Gear wheels. See also Fig. 532.

The *train of gear wheels* of Fig. 252 has a very high mechanical advantage. The wheel B makes one revolution in the

same time as wheel A, upon which the effort acts. But wheel C makes only that fraction of a revolution which is equal to

$$\frac{\text{number of cogs in } B}{\text{number of cogs in } C}.$$

The same is true of wheel F, which revolves only a fraction as rapidly as D. The wheels A and G are essentially wheel and axle. The total mechanical advantage of the train of gear wheels equals

$$\frac{\text{radius of } A}{\text{radius of } G} \times \frac{\text{No. of cogs in } C}{\text{No. of cogs in } B} \times \frac{\text{No. of cogs in } F}{\text{No. of cogs in } D}.$$

Gear wheels are much used to vary speed. If a wheel which has 32 gear teeth is in mesh with another wheel that has only 8 teeth, or cogs, then the second one will turn four times around while the first one turns around once. (See Fig. 253.) In clocks, in meters, and in many machines, speeds are varied by means of gears. In the automobile, gears on the drive shaft mesh with gears on a

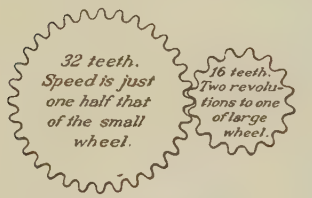


Fig. 253. — Gears may be used to vary speed.

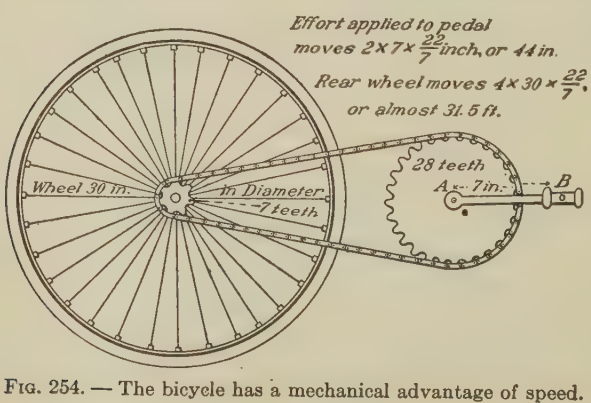


Fig. 254. — The bicycle has a mechanical advantage of speed.

countershaft when one shifts gears in driving. (See Fig. 756.) In the bicycle, for example, the sprocket wheels on separate shafts are connected by a chain. If the front wheel has 28 sprockets, and the rear one has only 7, then the rear wheel will make four revolutions while the pedals are making one complete turn. (See Fig. 254.)

When the screw S of the *worm wheel*, shown in Fig. 255, is given one complete turn, the wheel W turns through $\frac{1}{n}$ of a revolution, n being the number of cogs in the wheel W. Let l equal the length of the crank lever, or the radius of wheel R, and r the radius of the axle A; then the mechanical advantage of the worm wheel equals $\frac{nl}{r}$.

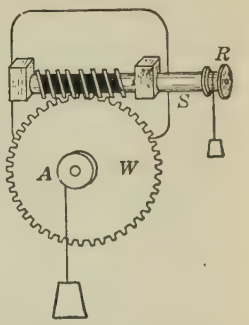


FIG. 255. — Worm gear. (See also Fig. 769.)

Some motor trucks are worm driven. A worm, or endless screw, on the drive shaft is turned by the engine. This worm turns a cogwheel on the rear axle. (See Fig. 769.)

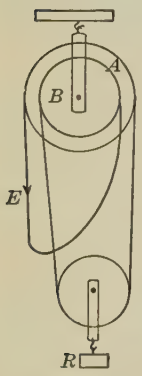


FIG. 256. — Differential pulley. Diagram.

In garages, boat houses, etc., the differential pulley finds extensive use for hoisting heavy objects. It is a machine which has a high mechanical advantage, but its efficiency is not very large.

The *differential pulley*, Fig. 256, consists of two wheels of unequal diameter turning on the same axis, and a movable pulley. An endless chain is used, and there are projections on the rim of the wheels into which the links of the chain fit, so that slipping is prevented. While effort E shortens the chain

by winding on the wheel A a length of chain equal to its circumference C, a length of chain is unwound from B equal to c, the circumference of wheel B. The chain is thus shortened by a distance equal to $C-c$. Although the chain is shortened by an amount equal to $C-c$, yet the resistance, which is attached to a movable pulley, is lifted a distance equal to $\frac{1}{2}(C-c)$. Thus, De equals C, the circumference of the large wheel; and Dr equals $\frac{1}{2}(C-c)$, which is one half the difference between the circumferences of the two wheels. Whence, M.A. $=\frac{2C}{C-c}$. (See Fig. 257.)

Fig. 257. — Commercial type of differential pulley.

The *steam shovel*, Fig. 258, is a compound machine that one sees everywhere. It is used to excavate for foundations of large buildings, make cuts or fills along railroad beds, dig canals or dredge waterways, scoop up ore, coal, and crushed rock and load them on freight cars, and to strip off the surface layers of earthy materials that are often found covering coal beds or iron ores. The buckets of the very large shovels hold 6 or 8 cu. yd. The student will find it interesting to see how many simple machines he can pick out in the picture of the steam shovel.

205. Efficiency of Simple Machines. Since it is impossible to eliminate friction, the efficiency of a machine can never be quite 100%. In the various types of levers, the efficiency may be nearly 100%, because the friction is so small. In the problems we have had where the weight of the lever is a help, it might appear as if the efficiency in such cases was really more than 100%. But we must remember that potential energy is being stored up in such a lever when we lift it into position.

The efficiency of the block and tackle is usually not more

than 60%. The rigidity of the ropes, the friction of the wheels, and the weight of the movable block all combine to lower the efficiency of this simple machine. The efficiency

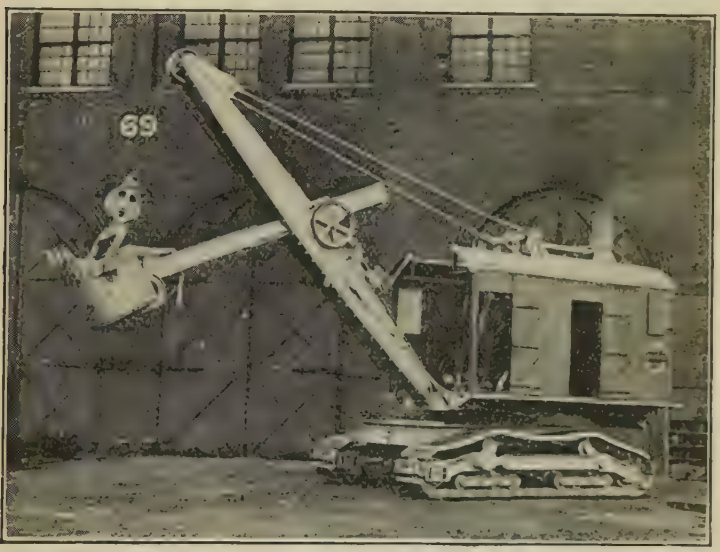


FIG. 258. — The steam shovel scoops up from 1 to 8 cu. yd. of material at a time.

of the inclined plane may be nearly 90%, if the surface is very smooth. The efficiency of the jack-screw may be as low as 25%.

I. WINDMILL. WATER WHEELS

206. The Windmill utilizes the kinetic energy of the wind to perform various kinds of work, especially the pumping of water. (See Fig. 259.) The blades are set in the wheel at such an angle that the force of the wind is resolved into two components, one causing the wheel to rotate rapidly. The vane V keeps the plane of the wheel at right angles to the direction from which the wind is blowing.

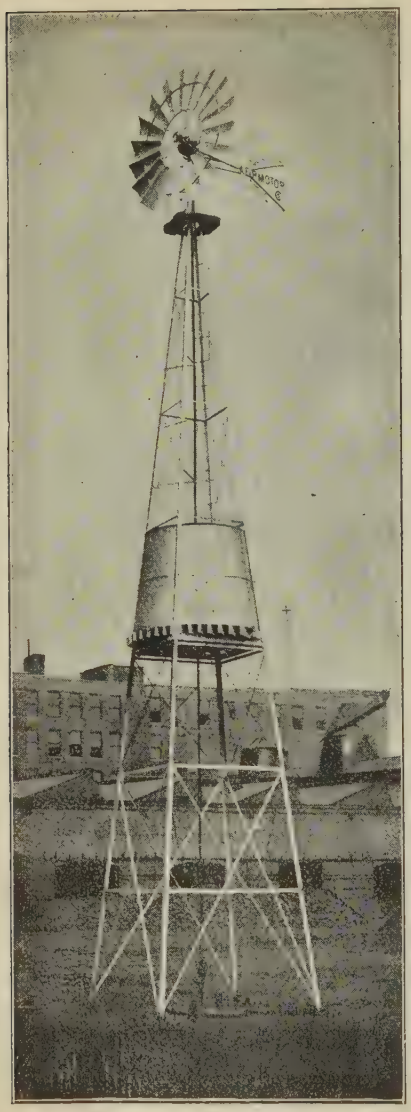


Fig. 259. — The windmill.

207. The Overshot Water Wheel, Fig. 260, uses the potential energy of the water at *R*. The work put into the machine is equal to the weight of the water flowing over the wheel times the distance the water falls. (Same as diameter of wheel.) The efficiency of this type of wheel is often as high as 80%. It is used in mountainous regions where the fall is considerable, but the supply of water is not very great.

208. The Undershot Water Wheel, Fig. 261, utilizes the kinetic energy of flowing water. It is used where the supply of water is abundant and the fall is slight. Its efficiency is usually about 25%. When the water is directed from a nozzle against the blades, an efficiency of 80% is sometimes obtained. The Pelton wheel, Fig. 262, is an example. Fig. 263 shows a large Pelton

wheel that was built for installation at Los Angeles, California.

The *water motor*, Fig. 264, works on the same principle as the Pelton wheel. If the pressure of the water from the mains is rather high, a small motor attached to a faucet furnishes sufficient power to operate lathes, grinding wheels, and polishing wheels, or to turn sewing machines.

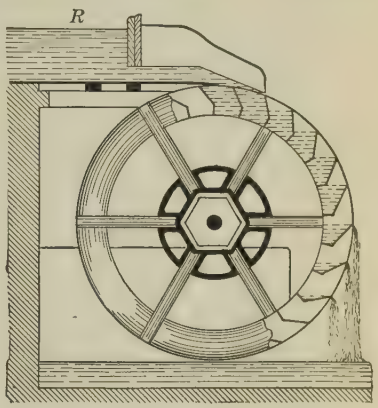


FIG. 260. — Overshot water wheel.

209. The Water Turbine. Of the various types of water

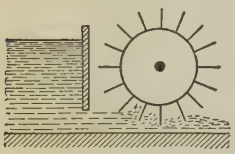


FIG. 261. — Undershot water wheel.

wheels, the turbine, which was invented in France in 1833, is most extensively used. In one type the wheel, which is mounted on a vertical axis, receives water through several openings from a penstock which is supplied by a turbine pit. (See Fig. 265.) A set of fixed blades in the case directs the water so that it strikes the blades of the wheel at right angles or nearly so, Fig. 266. The efficiency of the turbine may be as high as 90%. Fig. 267 shows a large runner made for use at Keokuk, Iowa.

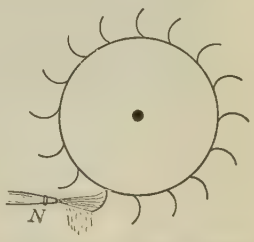


FIG. 262. — Pelton water wheel.

210. Transmission of Power. In a machine shop, we observe that some of the machines are "power" or *driving* machines.

On the other hand, such machines as lathes, polishing wheels, planers, saws, and grinding wheels are *driven* machines. Several methods are used for the transmission of power

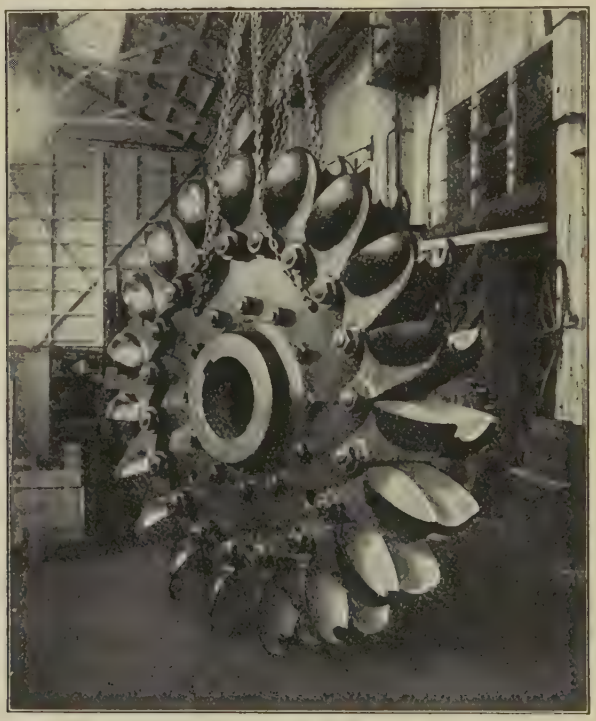


FIG. 263. — Pelton water wheel. This wheel is designed for the Big Creek project of the Southern California Edison Company at Los Angeles. It operates under a head of 1860 ft. of water and develops 22,500 H.P. at 375 revolutions per minute.

from the *driving* to the *driven* machines. Sometimes the driving shaft is connected with the machine by a train of gear wheels. An endless chain may be used; it passes from one sprocket wheel to another. The bicycle is an example. For short distances, belts and pulleys are used for power trans-

mission. Connected as in Fig. 268, both wheels turn in the same direction. A twisted belt, such as that shown in Fig. 269 causes the wheels to turn in opposite directions. The ratio of the speeds at which the belt wheels rotate is *inversely* proportional to the circumferences of the wheels. This makes it easy to increase or decrease the speed of a machine by changing the relative diameters of the belt wheels. For example, if wheel *A* of Fig. 268 has a diameter of 10 in. and wheel *B* has a diameter of 5 in., then *B* will make *two* revolutions while *A* is making *one*. The gasoline engine of an automobile furnishes power to drive the machine. Before the car can move, the "power" must be transmitted in some way to the rear wheels. Figs. 756 and 759 show how such transmission is usually accomplished by gear wheels of varying diameters. Compressed air and electricity are other methods used for power transmission.

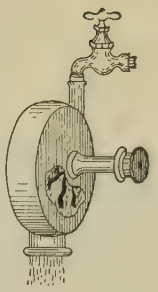


Fig. 264. — Water motor.

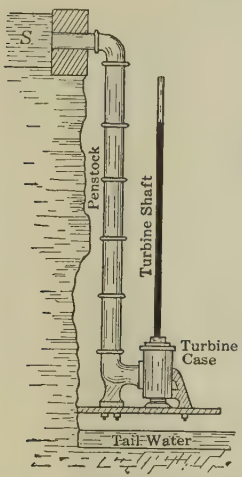


Fig. 265. — Turbine, showing method of installation.

211. The Cam or Eccentric. Very often it is desirable to change a rotary motion into a to-and-fro motion, or vice versa. When a sewing machine is operated, the treadle moves up and down, but the band wheel is given a rotary motion. The lower end of the rod

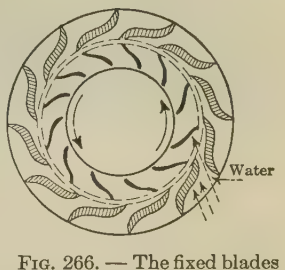


Fig. 266. — The fixed blades direct the water against the movable blades.

that connects the treadle with the band wheel moves up and down, or its motion is *reciprocating*. The upper end is attached to the band wheel at some point a short distance from the center (eccentric) upon which the wheel rotates.

FIG. 267. — A 10,000 H.P. turbine runner for the Mississippi River Power Company.

Fig. 270 shows that while the end of the rod A moves up and down, the other end B describes a small circle whose diameter just equals the translatory motion of A. By a belt the power is transmitted to the hand wheel, which in turn

controls another eccentric that causes the needle to move up and down. The automatic bobbin winder is another example

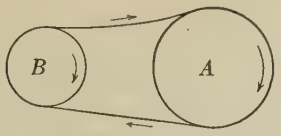


FIG. 268. — Both wheels rotate in the same direction.

FIG. 269. — Belt transmission. Driving and driven wheels turn in opposite directions.

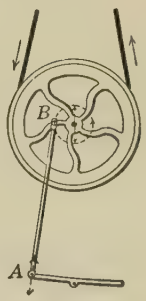


FIG. 270. — Cam, or eccentric, changes to-and-fro motion into a rotary one.

of the principle of the *cam*, or *eccentric*. The valves of a steam engine and also those of the gas engine are controlled by the cam, or eccentric.

SUMMARY

A machine is a device used to transform or transfer energy. Theoretically, input equals output. In practice, input exceeds output. Effort times effort distance equals resistance times resistance distance.

$$\text{M.A.} = \frac{\text{resistance}}{\text{effort}};\ \text{it also equals}\ \frac{\text{distance effort moves}}{\text{distance resistance moves}}.$$

The efficiency of a simple machine equals

$$\frac{\text{useful work accomplished}}{\text{total work expended}}.$$

In all classes of levers the effort : resistance = resistance arm : effort arm. $\text{M.A.} = \dfrac{\text{length of effort arm}}{\text{length of resistance arm}}$.

The mechanical advantage of a block and tackle equals the number of strands supporting the movable block.

In the law of the wheel and axle, $E : R =$ circumference of axle : circumference of wheel. The diameters or radii may be substituted for the circumferences.

When the force is applied parallel to the plane, effort : resistance = height of plane : length of plane. If the force acts parallel to the base, then $E : R =$ height : base.

In the use of the screw, the effort : resistance = the pitch : the circumference described by the effort.

QUESTIONS

1. What keeps the band wheel of a sewing machine moving during the short period between the downward and upward thrusts? Compare the relative speeds of the band wheel and the hand wheel of your sewing machine.

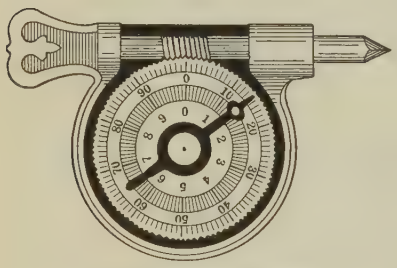


Fig. 271. — Speedometer.

2. How is friction an advantage in the use of a jack-screw? In what way is it a disadvantage?

3. Make a list of ten simple machines used about the household and classify them.

4. Explain how the speedometer shown in Fig. 271 can be used to determine the number of revolutions per minute?

5. The turnbuckle of Fig. 272 acts upon one rod which has a right-handed screw; it also acts upon another rod which has a left-handed screw. If each rod has 12 threads to the inch, how much is the space between the ends increased or decreased by one complete turn of the turnbuckle?

Fig. 272. — Turnbuckle.

6. How would you change a to-and-fro motion into a rotary motion?

7. What is meant by a "high gear" bicycle?

8. What is the meaning of the expression, "The gear ratio in the differential of an automobile is 4.5"?

9. Which gives the greater braking force, brake bands acting on a 12-in. drum or on a 16-in. drum? Explain.

PROBLEMS

1. The nut that tightens the handle bars of a bicycle has 10 threads to the inch. A boy uses a wrench 7 in. long to tighten the nut and exerts a force of 40 lb. What is the force that actually tightens the nut?

2. A plumber cut 12 threads on a pipe to an inch of its length. If he uses a Stillson wrench 21 in. long to connect a valve to this pipe, what mechanical advantage does he have?

3. The pitch of a jack-screw is 0.2 in.; 20 lb. of effort are applied to a lever attached to the head of the screw. If the circumference described by the effort is 9 ft., what weight can be lifted?

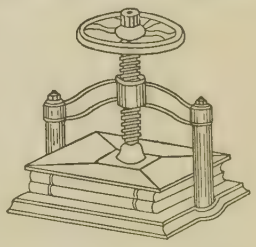


Fig. 273. — Letter press.

4. The threads of a letter press are $\frac{3}{16}$ in. apart. If a force of 40 lb. is applied to the rim of a 14-in. wheel, what is the force of compression? (See Fig. 273.)

5. The threads of a jack-screw are $\frac{3}{8}$ in. apart. The screw is operated by a lever 2 ft., 4 in. long. If the effort applied is 100 lb., what resistance can be overcome, neglecting friction?

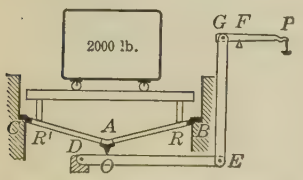


Fig. 274. — Platform scales.

6. A jack-screw is operated by a lever 18 in. long. The pitch of the screw is $\frac{1}{4}$ in. If 40 lb. are required to lift a weight of 4500 lb., what is the efficiency of the screw?

7. In the hay scales of Fig. 274, the levers AB and AC are each 8 ft. long; BR and CR' are each 8 in. long; DE is 10 ft., and OD is 1 ft.; GF and PF are 9 and 30 in. long respectively. What weight at P is needed to counterbalance a weight of 2000 lb. on the platform?

8. The diameters of the wheels of a differential pulley are 18 and 16 in. respectively. What is the mechanical advantage? If

100 lb. must be applied to the rim of the larger pulley to lift a weight of 1200 lb., what is the efficiency?

9. A ladder used as a scaffold is 12 ft. long and weighs 100 lb. Each end is supported by a block and tackle in which 3 strands support the movable block. If the painter, who weighs 168 lb., stands 1 ft. from one block, with what force must he pull to raise the end of the ladder?

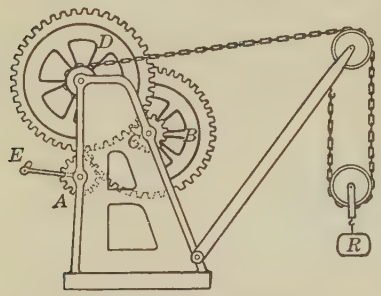


FIG. 275. — Builder's crane.

10. The front sprocket wheel of a bicycle has 28 sprockets; the rear wheel has 7. If the bicycle wheel has a diameter of 30 in., how far does the bicycle move forward with one complete turn of the pedals? If the pedal revolves at the rate of 60 times per minute, at what speed per hr. is the bicycle driven?

11. The lever of a worm wheel similar to that shown in Fig. 255 is 2 ft. long. The wheel has 90 cogs. If the axle has a diameter of 4 in., what load can be lifted by a force of 10 lb.?

12. The crane of Fig. 275 has a lever arm of 20 in. The gear wheels A, B, C, and D have 12, 60, 12, and 72 cogs respectively. If the axle has a radius of 4 in., what is the mechanical advantage of the crane?

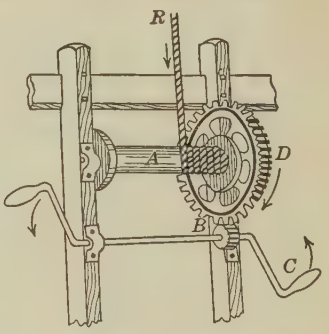


FIG. 276. — Derrick.

13. Fig. 276 shows a simple derrick. The crank C is 2 ft. long. The axle upon which the rope winds is 4 inches in diameter. There are 60 cogs in D and 10 in B. If the end of the rope R is attached to a system of pulleys in which 5 strands support the movable block, what force at C will be required to lift a weight of 12,000 pounds?

CHAPTER 9

HEAT—THERMOMETRY

Vocabulary

Temperature, degree of heat or cold.
Centigrade, one hundred degrees.
Bore, the interior diameter of a tube.

212. Nature of Heat. Prior to the nineteenth century, heat was thought to be a weightless fluid, called *caloric*. When in 1799, Sir Humphry Davy melted two pieces of ice by rubbing them together, he proved that heat is a form of energy. We have learned that all matter is composed of very small particles called molecules, which are in constant motion. As the velocity of the molecules of a body increases, its temperature rises. The Indians formerly started fires by rubbing two sticks together until the heat produced by friction enkindled them. Boy Scouts now use "fire-sticks" in a similar manner to start fires when camping. Rubbing the hands together increases molecular motion and warms the hands. Conversely, a decrease in molecular velocity causes a fall in temperature. From a consideration of these facts, we may define heat as kinetic energy due to molecular motion.

213. Sources of Heat. (*a*) *The sun.* We get heat from many sources, but the heat from the sun is the most important. Directly or indirectly, nearly all the heat we receive can be traced to the sun as its origin. Plants require heat for their growth, and animals are dependent upon plants. Of the total heat which the sun gives off, it is estimated that the earth receives only $\frac{1}{2,000,000,000}$.

(*b*) *Heated interior of earth.* Molten rock issues from

volcanoes, and boiling water spouts from geysers. Deep wells and mines also furnish proof that the interior of the earth is still highly heated. The temperature in the Calumet and Hecla copper mine, which is over one mile deep, is so high that even with the use of compressed air for ventilation, the men work in two-hour shifts.

(*c*) *Chemical action* is a very important source of heat. We depend upon the combustion of wood, coal, etc., to keep our houses warm in winter. The oxygen of the air combines with the burning fuel, while both heat and light are evolved. The oxygen which we breathe unites with the food we eat to keep the temperature of the body at about 98.6° F.

(*d*) *Mechanical energy* can be transformed into heat. *Friction*, *impact*, and *compression* are examples of the methods by which mechanical energy may be used to produce heat. It is obvious that in all these cases the velocity of the molecules is increased. Rubbing the head of a match on emery paper heats it by friction to its kindling temperature. A bullet fired against a hard steel plate is apt to be melted by the heat due to impact or collision. As we pump up a pneumatic tire, the pump becomes hot. This is due partly to friction, but more largely to the compression of the gas in the cylinder.

214. Heat and Temperature. The amount of heat a body has and its temperature are two very different things. A burning match has a much higher temperature than a steam radiator, but it is not so useful for heating a room. A cup of water taken from a tank of boiling water has the same temperature as the water in the tank, but it has less heat. Ten pounds of water at 80° F. will melt more ice than one pound of water at 100° F. The *temperature*, or the *average kinetic energy* of the molecules, in the pound of water is higher than it is in the ten pounds, but the *heat*, or the *sum total of all the kinetic energies*, is greater in the larger volume

of water. If a small radiator with only a few sections has the *same temperature* as a large radiator with many sections, it cannot supply as much heat to a room. For large rooms we use larger radiators than for small rooms, even when they are to be heated to the same temperature. From these observations, we see that it is possible for a body to have a high temperature, and little heat; it may have a high temperature and much heat; it may have a low temperature and little heat; or it is possible for it to have a low temperature and a large quantity of heat. (See Fig. 277.) We measure temperature in *degrees*, but we measure heat in *calories*.

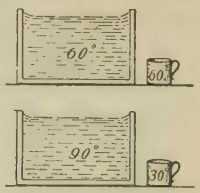


FIG. 277. — Top. Equal temperature, unequal heat. Bottom. Unequal heat and temperature.

215. Sensation and Temperature. The terms "hot," "cold," and "warm" are used to indicate temperature. Their use is relative, however, and they often mean very little. A room that feels comfortable to a person who has been resting seems very warm to one who has been exercising vigorously. Given three adjoining rooms, "hot," "warm," and "cold" respectively. One person going from the first room to the second finds it "cold," while the same room feels "warm" to another person entering it from the third room. Suppose we put one finger of the right hand into a tumbler of *hot* water, and a finger of the left hand into a tumbler of *ice cold* water, and then dip both of them into a third tumbler containing water that is *lukewarm*. The lukewarm water will feel cold to the finger of the right hand, but it will feel warm to the finger that had been in the ice water. Thus the same water feels both hot and cold at the same time. Since our *temperature sense* is so unreliable, we make use of thermometers to measure the temperature, or degree of heat.

216. The Air Thermometer. One of the simplest of the early thermometers was the invention of the famous Galileo.

The operation of this thermometer depends upon the fact that air expands readily when it is heated. To a glass bulb a long glass tube is attached as shown in Fig. 278. The lower end of the tube dips into some colored liquid. When the bulb is warmed, the air inside expands and some of it escapes. As the bulb is cooled some of the liquid rises in the tube. Such a thermometer is very sensitive to changes in temperature, but of course it would need to be corrected each time for changes in air pressure.

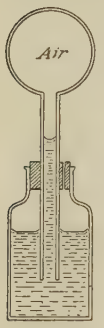


Fig. 278.—Air thermometer.

217. The Mercury Thermometer. Although the mercury thermometer is less sensitive than the air thermometer, it is not affected by varying air pressures. In the construction of such a thermometer, a bulb is blown at one end of a thick-walled glass tube of small, uniform bore. (See Fig. 279.) The bulb and part of the stem are then filled with mercury. When the bulb is heated to a temperature a few degrees higher than the maximum temperature for which the thermometer is to be used, the tube is then sealed at *A*. All the air has thus been expelled from the tube, and as the mercury contracts upon cooling, a vacuum is formed at the top of the tube. A tube and bulb partially filled in this manner needs only to be graduated to make it a finished thermometer.

Fig. 279.—Thermometer bulb and stem.

218. Fixed Points. Before a thermometer can be graduated, some fixed points or definite temperatures must be selected. The *freezing point* and the *boiling point* of water are chosen, since these fixed points can be quite easily determined. To determine the freezing point, the bulb and lower part of the stem are packed in

melting ice. The freezing point of water and the melting point of ice have the same temperature. Hence we use melting ice in this case, since it is much more convenient to use than freezing water. The lowest point to which the mercury falls when the bulb and lower part of the thermometer tube are packed in *melting* ice is marked the *freezing point.* (See Fig. 280.) This fixed point may be engraved on the stem of the thermometer, or on a scale to which the bulb and tube are attached.

FIG. 280. — Freezing point determination.

To find the boiling point, the thermometer is suspended in the steam arising from boiling water. (See Fig. 281.) Since the temperature at which water boils varies with the pressure, steam arising from water boiling under a pressure of 76 cm. of mercury must be used. The highest point to which the mercury rises is marked the *boiling point.*

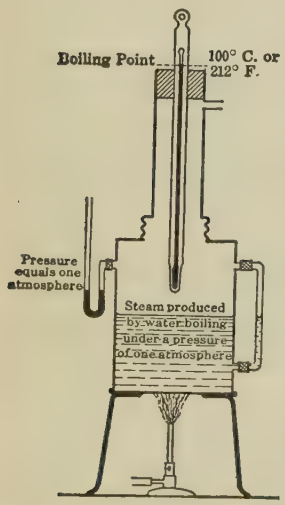


FIG. 281. — Boiling point determination.

219. Centigrade and Fahrenheit Scales. Several scales are used in graduating thermometers. The Centigrade, or Celsius, scale is used almost exclusively in foreign countries and for *scientific* work in the United States. On the Centigrade thermometer the freezing point is marked *zero* and the boiling point 100. The space between the fixed points is divided into 100 equal parts called *degrees.*

On the Fahrenheit thermometer, which is used in the United States for weather observations, the freezing point is marked

32° F., and the boiling point 212° F. The space between the fixed points is then divided into 180 equal parts, or degrees. The difference in temperature between the freezing point and the boiling point of water is 100 Centigrade degrees or 180 Fahrenheit degrees. Therefore 100 Centigrade degrees must equal 180 Fahrenheit degrees, and 1° C. equals 1.8° F. (See Fig. 282.)

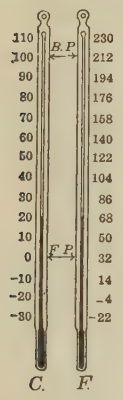


FIG. 282.—C. and F. scales compared.

220. To Convert One Scale Reading into Another. Sometimes we find it necessary to change the reading of a Centigrade thermometer to the corresponding reading on the Fahrenheit scale, or vice versa. If the Centigrade thermometer reads 20°, that means that the temperature is 20 Centigrade degrees above the freezing point, which is zero on this scale. But 20 Centigrade degrees equal 20×1.8, or 36 Fahrenheit degrees above the freezing point. Since the freezing point on the Fahrenheit scale is 32°, the reading on the Fahrenheit scale corresponding to 20° on the Centigrade scale is 36 plus 32, or 68° F. *To change Centigrade readings to Fahrenheit, multiply the Centigrade reading by 1.8, and add 32. To change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.* The formula in Appendix B may be used.

PROBLEM. Change −10° C. to Fahrenheit. Change −58° F. to Centigrade.

Solution. $-10 \times 1.8 = -18; -18 + 32 = 14$. Hence, −10° C. equals 14° F. In No. 2, $-58 - 32 = -90; -90 \div 1.8 = -50$° C. Therefore, −58° F. equals −50° C.

221. Limitations of the Mercury Thermometer. Since mercury freezes at −39° C., it cannot be used to measure temperatures below that point. For lower temperatures alcohol is often used. The freezing point of alcohol is

−130.5° C.; alcohol is often colored red or blue and used in thermometers for very cold countries to measure temperatures below the freezing point of mercury. For *very* low temperatures a gas thermometer is used. (See Fig. 283.) The hydrogen gas with which the bulb is filled contracts upon being cooled, and the mercury falls in the tube *C*. The tube *C* is then lowered until the mercury reaches the former level *B*. The temperature is determined by the *change of pressure* required to keep the volume of hydrogen gas constant.

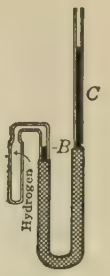


FIG. 283.—Gas thermometer.

The boiling point of mercury is 357° C.; therefore the mercury thermometer is not suitable for measuring very high temperatures. A gas thermometer may be used, or electrical instruments such as the platinum resistance thermometer and the pyrometer.

222. Special Thermometers. The normal temperature of the human body is 98.6° F., or 37° C. Since the variation in temperature is never more than a few degrees, the *clinical* thermometer used by physicians has only a short scale, usually graduated from 92° F. to 110° F. The tube is constricted just above the cylindrical bulb. When the mercury expands, it is easily forced past this constriction, but as it cools the cohesion between the mercury molecules is not great enough to pull the thread of mercury back past the constriction. Thus the top of the mercury column indicates the highest temperature registered. After the reading has been taken, the thermometer must be given a quick jerk to shake the mercury back into the bulb and set it for the next reading. (See Fig. 284.)

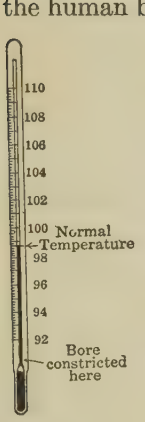


FIG. 284.—Clinical thermometer.

Maximum and minimum thermometers are used at Weather Bureau stations to show the highest and lowest tempera-

tures during each day. One type of *maximum* thermometer is constructed just like the clinical thermometer. It is set

FIG. 285.—Minimum thermometer.

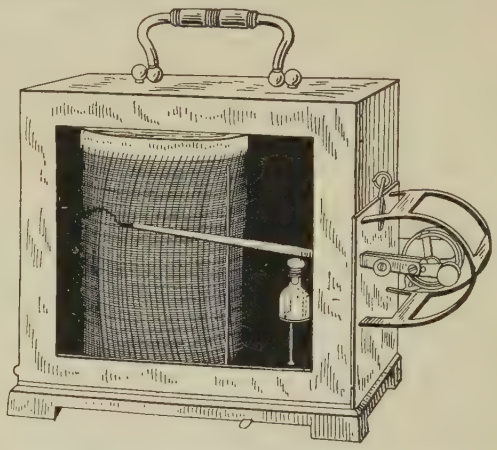


FIG. 286.—Thermograph, or self-registering thermometer.

at a certain hour of the day by shaking the mercury down into the bulb. As the temperature increases the mercury

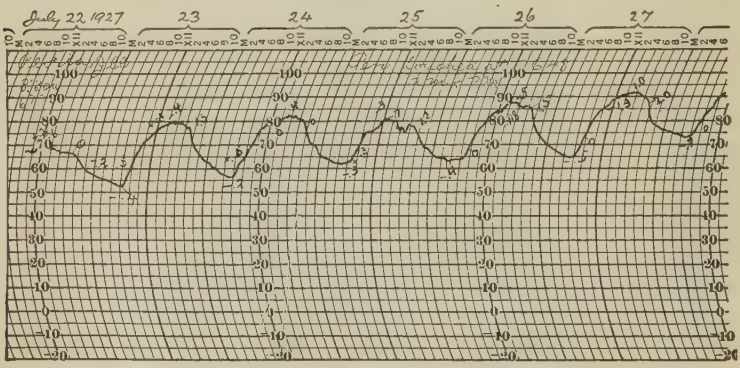


FIG. 287. — The graph shows the regular daily variations in temperature for a week at Peoria, Illinois.

rises in the tube; it will stand in the tube at the highest point reached during the day.

In the *minimum* thermometer, the bulb is filled with alcohol. The surface tension of the alcohol drags a small index along the tube as the alcohol cools and contracts. The index is left at the lowest point reached during the time interval, since the alcohol flows past it upon expanding. (See Fig. 285.)

Self-registering thermometers, such as that shown in Fig. 286, are used to keep a continuous record of the temperature. The cylinder, which is turned by clock-work, makes one revolution per week. A pen or pencil carried by the lever

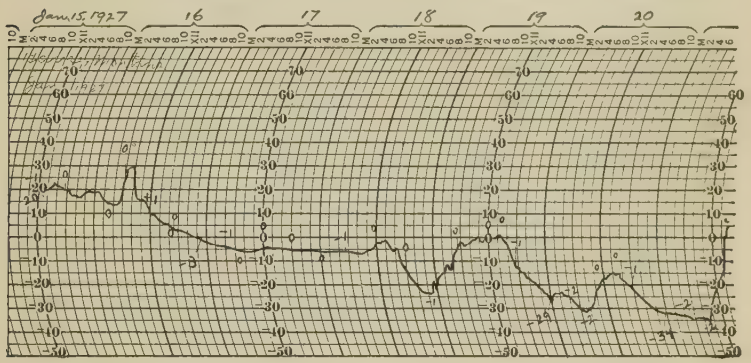


FIG. 288. — The graph shows a decided cold wave for the week of January 15, 1927, at Havre, Montana.

arm records the temperature on a sheet of ruled paper, which is wound on the cylinder. Figs. 287 and 288 show how such charts can be used to indicate the temperature for any particular hour of the day or week. A chart of this kind may be dated and kept as a permanent record.

SUMMARY

The sun, the interior of the earth, chemical action, friction, impact, and compression are the chief sources of heat.

Heat is the sum of the kinetic energies of all the molecules of a body. The temperature of a body is the average kinetic energy of its molecules.

Sensation is an unreliable method of determining temperature. A thermometer is an instrument devised for that purpose.

To change Centigrade readings to Fahrenheit, multiply the reading by 1.8 and add 32; to change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.

Special thermometers are constructed to show the maximum or minimum temperature for any given period, usually 24 hr.

QUESTIONS

1. Why do sparks sometimes fly from a car wheel when the brakes are applied?

2. Sometimes the brakes of an automobile catch fire when the driver is descending a long grade. Explain, and tell how such a condition may be avoided.

3. Give an example of a body that has a low temperature and a large quantity of heat. Give an example of a body that has a high temperature but contains little heat.

4. What important objection is there to the air thermometer?

5. Why must a thermometer tube be of uniform bore?

6. Should a thermometer have a spherical or a cylindrical bulb? Give a reason for your answer.

7. Air must be cooled before rain falls. At the tropics the air currents are descending. How do you account for the arid regions in Australia?

8. How does the size of the bulb of a thermometer affect its sensitiveness? What other factor affects the sensitiveness of an ordinary thermometer?

9. What properties should a liquid have to make it suitable for use in a thermometer?

10. Occasionally a train is delayed because of a "hot box." What is a "hot box," and how is it caused?

11. Why does the mercury in a thermometer drop a fraction of a degree before it begins to rise when the bulb is plunged into hot water?

PROBLEMS

1. The temperature of the electric arc is about 3600° C. What is the corresponding Fahrenheit temperature? 6512°

2. If alcohol freezes at −130° C., calculate its freezing point on the Fahrenheit scale. -202°F.

3. Change −182° C., the boiling point of liquid air, to Fahrenheit. -295°F

4. Reduce the following Fahrenheit temperatures to Centigrade: 170° F.; −299° F.; 6332° F.; −10° F.; 80° F.; −252° F.; −430° F. +76.6°-183.9°+26.7°-23.3°-26.6°+157.7°-256.6°

5. Reduce the following Centigrade readings to Fahrenheit: 1600° C.; −273° C.; −190° C.; −40° C.; 4000° C.
2912° -459.4° -310° -40° 7232°

CHAPTER 10

HEAT—EXPANSION

Vocabulary

Corrugated, formed into folds or furrows.
Coefficient, a number used as a factor.
Compensated, opposing forces are balanced.
Alloy, a substance composed of two or more metals.
Superficial, pertaining to surface or area.

223. Effects of Heat. In the preceding chapter we learned that the temperature rises when molecular motion is increased. In the study of heat, we are interested in the effects that heat produces. When heat is applied to ordinary matter, several different effects may be produced: 1. In some cases the temperature rises while heat is being absorbed. 2. Sometimes the absorption of heat causes a solid to melt, or a liquid to change to a gas. For example, ice melts as it absorbs heat, and water changes to vapor. 3. In the cooking of foods, heat causes chemical changes to occur. In fact many chemical changes are started by the application of heat. 4. The size of an object nearly always increases when it is heated. The mercury in a thermometer tube is a familiar example. 5. Heat sometimes produces an electric current. One method of measuring temperature consists in measuring the strength of the electric current that is produced when two unlike pieces of metal in close contact are heated.

224. Expansion of Solids. Telephone wires sag more in summer than they do in winter. Cement walks often buckle in hot weather. With very few exceptions, solids expand when heated, and contract when cooled. They not only increase in length, but also in breadth and thickness. The space between the ends of railroad rails is greater in winter

than in summer. Sometimes wires used for fences and for telephone or telegraph break in winter, as they contract so strongly upon cooling. (See Fig. 289.) Carriage tires are heated before they are placed on the wheel. They contract upon cooling, and produce a tight fit. If the metal ball shown in Fig. 290 is put through the ring and then heated, it cannot be removed without cooling the ball or heating the ring. Rubber is an exception to the general rule that solids expand when heated.

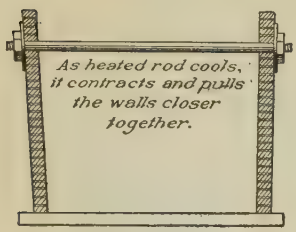


FIG. 289.—Rod contracts upon cooling.

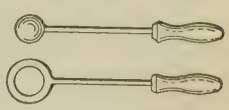


FIG. 290. — Cold ball passes through ring, heated ball cannot.

225. Coefficient of Linear Expansion. Some solids expand much more when heated than others do. For example, a piece of aluminum wire one foot long will expand rather more than twice as much as a piece of iron wire of the same length when each one is heated through one degree Centigrade. Experiment shows that 1 ft. of aluminum expands 0.000023 ft. when its temperature is raised one degree Centigrade. The *increase in the length of a solid when unit length is heated one degree Centigrade is called its coefficient of linear expansion.* Of course 1 *cm.* would increase 0.000023 *cm.* when heated 1° C.

The coefficient of linear expansion of some common solids is given in the accompanying table:

COEFFICIENT OF LINEAR EXPANSION. (1° CENTIGRADE)

Quartz . .0000005	Iron . . .000011	Silver . . .000019
Invar . . .0000009	Steel . . .000013	Tin . . .000021
Pyrex . . .000003	Gold . . .000014	Aluminum .000023
Glass . . .000009	Copper . .000017	Zinc . . .000029
Platinum . .000009	Brass . . .000019	Lead . . .000029

The coefficient of expansion per degree Fahrenheit equals $\frac{5}{9}$ of the value given in the table. Some metals do not expand the same at all temperatures. That is, they may expand slightly more or slightly less when heated from 0° to 1° C. than they do if heated from 20° to 21° C. In most cases the difference is so slight we may consider it negligible.

It is important to remember that a solid expands in all directions. If only the length increased, solids would be distorted. A thick glass breaks when put in hot water because the surface expands before the inner part of the glass is heated. Glass does not break when it is heated uniformly.

Problem. An iron rod is 65 cm. long at 0° C. How much will it expand when heated to 80° C.? What will be its length at 80° C.?

Solution. From the table we see that 1 cm. of iron expands .000011 cm. when heated 1° C.; 65 cm. will expand $65 \times .000011$ cm., or .000715 cm., when heated 1° C.; the change in temperature is 80 degrees, so the actual increase would be $80 \times .000715$ cm., or .0572 cm. The length of the rod at 80° C. would be 65.0572 cm. (Original length plus expansion.)

226. How Coefficient of Expansion is Measured. The expansion of a solid is so small that it is difficult to measure directly. One end of a rod 70 or 80 cm. long may be clamped and a spherometer placed in contact with the other end. The spherometer may be read, first when the rod is at room temperature and then again when the rod is heated to 100° C. by means of steam. The difference between the two readings shows the increase in the length of the entire rod when heated from room temperature to steam temperature. The actual increase *per centimeter per degree* can then be calculated.

Sometimes multiplying devices are used to read the expansion more accurately. In Fig. 291, a groove near one end of a metal tube of which we wish to find the increase in length is placed upon a knife-edged block which holds this

end of the tube stationary. The other end rests upon a small rod to the end of which a pointer is attached. When steam is passed through the tube, it expands, rolling the

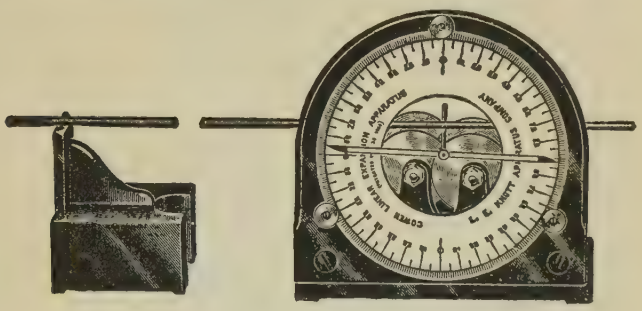


Fig. 291. — Cowen's apparatus.

rod and turning the pointer through a certain number of degrees. The actual number can be read by means of the circular protractor. Suppose the rod has a diameter of 2.1 mm.; its circumference is 6.6 mm. If the pointer turns through only 60° of a circle, the tube must have expanded $\frac{60}{360}$, or $\frac{1}{6}$, of 6.6 mm. Its expansion turned the rod one-sixth of a complete revolution. Knowing the original length of the tube and the change of temperature, one can easily calculate the expansion for *unit* length for *one* degree Centigrade.

227. Applications. One end of a bridge is often supported on rollers to allow for contraction and expansion. (See Fig. 292.) Rivets are heated red hot before they are used to rivet two plates together. As they cool they contract and make a very tight joint. The expansion and contraction of metals is used to open and close valves. In one type of automatic water heater, a rod of invar is used inside a copper tube to regu-

Fig. 292.— Bridge expands when heated.

late the amount of gas needed to keep the water at the desired temperature, usually 140° F. (See Fig. 293.)

At one time platinum was the only metal known to have the same coefficient of expansion as glass. At that time two short pieces of platinum wire were used for the "lead-in" wires of electric bulbs. Thus the seal was not broken by

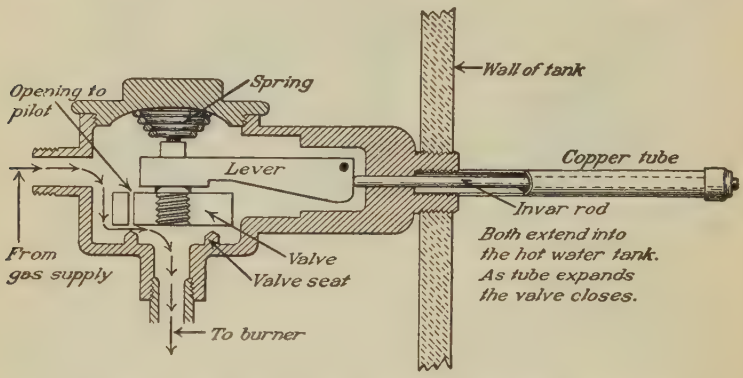


FIG. 293. — Thermostat to keep water at a constant temperature.

unequal expansion or contraction. Research engineers worked diligently in an effort to find a substitute for the expensive metal, platinum. They have developed an alloy of nickel and iron, which, when sheathed with copper, is very satisfactory.

The manufacturers of pyrex glass have learned what to use to lower the coefficient of expansion of their product and so reduce the danger of breakage from heat. Thick glass baking dishes are common, and pyrex glass is now extensively used in chemical laboratories.

228. Radiator Valves. Since two things cannot occupy the same place at the same time, the steam from a furnace cannot enter the radiators to heat them unless provision is made for the removal of the cooler air which the radiators contain. The sectional view of such a valve as shown in Fig. 294 may

help us to understand how the radiator valve opens to let the air out, but closes to prevent the escape of steam into the room. The metal capsule C contains a liquid which changes into vapor when it is heated by the steam. The vapor of this liquid exerts pressure against the walls of the capsule. The elasticity of the corrugated metal permits the top to be pushed upward until the opening in the valve is closed tightly when the radiator is hot. Such a valve opens again when the radiator cools.

FIG. 294.— Radiator valve.

229. The Compound Bar. If we take two flat strips of iron and brass, and rivet them together, the compound bar thus produced will bend when heated. (See Fig. 295.) Since the brass expands more when heated than the iron, it will be found on the outside of the curve. The bar will first straighten out and then curve in the opposite direction if it is cooled decidedly. Of course a compound bar made of any two metals having different coefficients of expansion will behave in the same manner.

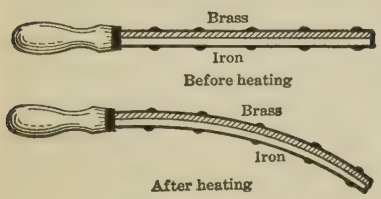


FIG. 295. — Compound bar.

230. Applications of Compound Bar. *The thermostat.* In some thermostats which are used to keep a constant temperature, a compound bar is used. One end is fixed; the other end makes or breaks an electrical circuit as the change of temperature causes the coiled bar to move the pointer back and forth. (See Fig. 296.) If the room grows too warm, the compound bar makes contact at C, and the

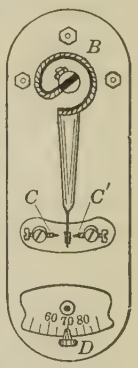


FIG. 296. — Thermostat keeps temperature constant.

drafts of the furnace are automatically closed. They are opened again when contact is made at C'. Thus a room may be kept at a constant temperature with a variation of only one or two degrees.

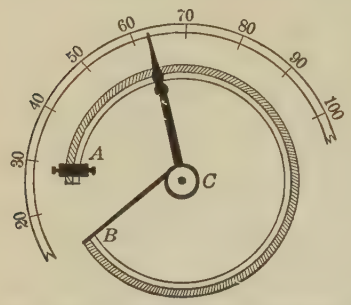


Fig. 297.— Metal thermometer is a compound bar.

Metallic thermometers. In Fig. 297 we see how a compound bar may be used as a thermometer. One end of the spiral is fixed at A; the other end at B is attached to a pointer which rotates about the axis C. The metal on the outside of the curve has the greater expansion. Many oven thermometers are of this type.

The balance wheel. When the balance wheel of a watch expands, the watch runs more slowly. The higher priced watches have compensated balance wheels. As the radius of the wheel, Fig. 298, expands and tends to slow up the movement, the compound bar bends just far enough to throw the loaded ends inward. This tends to accelerate the motion. It is possible to so adjust such a balance wheel that the effect of the increased radius is just nullified by the inward movement of the loaded ends. Such a watch is not affected by temperature changes.

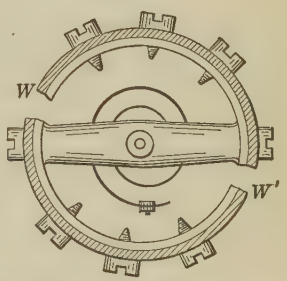


Fig. 298.— Compensated balance wheel.

The compensated pendulum consists of bars so arranged that one set tends to shorten the pendulum while the other set tends to lengthen it. Fitted with an ordinary pendulum, a clock will gain time in winter due to the contraction of the pendulum, and lose time in summer on account of its expan-

sion. Invar is sometimes used for such pendulums, but for very accurate clocks a pendulum like one of those shown in Fig. 299 must be used. In (*A*) the center of oscillation of the pendulum is lowered when the supporting rod expands, but the expansion of the mercury upward raises the center of oscillation by exactly the same amount that it was lowered. A clock with such a pendulum is not affected by temperature changes.

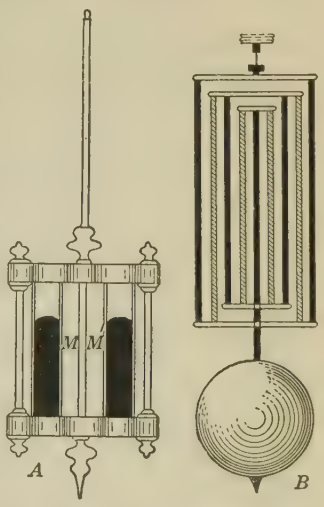


Fig. 299. — Compensated pendulums. *A*. Mercury. *B*. Bars of iron and brass.

In type (*B*) the light-colored rods are of brass and the dark of steel. The brass rods are shorter than the steel, but they have a higher coefficient of expansion. The expansion of the brass rods shortens the pendulum, but the expansion of the steel rods lengthens it. The rods may be so proportioned that one neutralizes the effect of the other, and the center of oscillation is neither raised nor lowered by any change of temperature.

231. Expansion of Liquids. If one fills a tank with gasoline on a cool evening, and then lets it stand in the sun the next day, some of the gasoline will overflow. Heat causes liquids to expand. We have already had examples of the expansion of mercury and alcohol in thermometers. When the housewife cans fruit or bottles grape juice, she fills the container full of the hot juices. Then the container is sealed. When it has cooled to room temperature, the liquid contracts until it no longer fills the container.

An apparatus similar to that shown in Fig. 300 is used to

measure the coefficient of expansion of liquids. With liquids we are not concerned with anything but their increase in volume. We measure their coefficient of *cubical* expansion, which is approximately *three times the coefficient of linear expansion.*

FIG. 300. — Liquid expansion.

Liquids have a higher coefficient of expansion than solids. This is obvious when we compare the expansion of mercury in a thermometer with the expansion of the glass. The amount of expansion of liquids varies considerably with the temperature, but the expansion of mercury is fairly uniform between 0° C. and 100° C. Otherwise the degrees on a thermometer would be unequally spaced.

The coefficient of cubical expansion of mercury is 0.00018, nearly seven times that of glass; of water, from 5° C. to 8° C., 0.00002; of water, 99° C. to 100° C., 0.00076; of alcohol, 0.0011; and of petroleum, 0.0009.

PROBLEM. 100 gallons of petroleum are measured at 0° C. What will be the volume of the petroleum at 30° C.?

Solution. $0.0009 \times 30 = 0.027$ gal., the expansion of 1 gallon when heated 30 degrees. $0.027 \times 100 = 2.7$ gals., total expansion. $100 + 2.7 = 102.7$ gals., the new volume.

232. Peculiar Expansion of Water. When water at 100° C. is cooled, it gradually contracts until a temperature of 4° C. is reached; it then expands as it is cooled from 4° C. to the freezing point. Of course when a substance contracts, its density is increased, since its mass is always constant. Therefore water has its greatest specific weight, 1.00000, at 4° C. At 0° C. its specific weight is 0.99987; at 20° C., its specific weight is 0.99825. We can find the *specific volume* of a body by dividing *one* by its specific weight. In the Metric system the specific volume is that volume of the body in c.c. needed to weigh 1 gm. The peculiar expansion of water is

best shown by a curve like that of Fig. 301. In this graph, the specific volumes of water are used as ordinates, and the temperatures as abscissas.

If water continued to contract until the freezing point were reached, the coldest water would sink to the bottom of the container. A pond would then begin to freeze at the bottom instead of at its surface. Lakes and rivers would freeze solid in winter and thaw out only a few feet at the surface in summer. Fish and other aquatic animals would perish. As it is, ice is not formed at

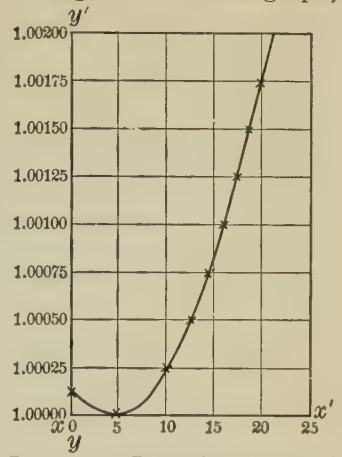


FIG. 301. — Expansion curve of water.

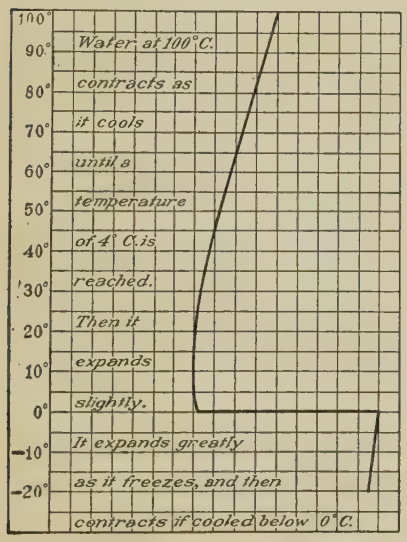


FIG. 302. — Contraction of water.

the surface until all the water is cooled to 4° Centigrade. The water at the bottom of a frozen pond or lake in winter is 4° Centigrade. Fig. 302 shows how a given volume of water would contract in cooling from 100° C. to 4° C., expand in cooling from 4° C. to 0° C., expand still more upon freezing, and then contract when the ice is cooled below 0° C.

233. Expansion of Gases. When bread or biscuit dough is put in

the oven, the gas used for leavening expands greatly during the heating. This expansion makes the dough rise. All gases expand when they are heated. We are concerned with the coefficient of cubical expansion only, or their increase in volume. Unlike liquids and solids, *all gases have the same coefficient of expansion*, and *it is uniform at all temperatures*. The value of this coefficient of cubical expansion is $\frac{1}{273}$ of the volume at 0° C., or 0.003665 per degree Centigrade. It is about 20 times as much as the coefficient of expansion of mercury and more than 59 times that of aluminum.

In 1787, Charles, a Frenchman, performed experiments proving that all gases expand the same amount when heated one degree, if the pressure is kept constant. Let us take a small glass tube, sealed at one end, and measure the air column inclosed by a globule of mercury M, as shown in Fig. 303, when the tube is immersed in ice water. Next we may measure the length of the air column when the tube is immersed in steam. We find that the air column has increased in length $\frac{100}{273}$ of its original length, when heated from 0° C. to 100° C. For each degree of temperature change, the expansion is $\frac{1}{273}$ of the volume at 0° C. When other gases are used, the same result is obtained. While Charles was the first to study the expansion of gases, the law sometimes bears the name of Gay-Lussac, who was the first to announce the law showing the relation of the volumes of gases to their temperatures.

FIG. 303. — Gas expansion.

234. How Expansion Affects Density. Heating a gas, a liquid, or a solid does not change its weight. Since, however, the volume is increased, the density must be decreased. For this reason we find the warmer, lighter air of a room near the ceilings instead of at the floor. In a hot water tank, the hot water accumulates at the top of the tank. Such a change

in the density of liquids and gases when they are heated is a very important factor in the distribution of heat.

When a confined gas is heated so that it cannot expand, the pressure which the gas exerts is increased. A balloon tire pumped up on a cool morning may show a gauge pressure of 35 lb. per sq. in. If the tire stands in the sun so that the temperature of the air inside is increased 20 or 30 degrees Centigrade, it may show a pressure of 38 or 39 lb. per sq. in. Raising the temperature increases the velocity of the molecules and causes an increased pressure.

235. Absolute Temperature. We know that gases expand when heated and contract when cooled. It is of interest to inquire how a gas will behave if we cool it below 0° C. It continues to contract, losing $\frac{1}{273}$ of its volume for every degree that it is cooled below zero. At −100° C., its volume is decreased by $\frac{100}{273}$; or it is only $\frac{173}{273}$ of its former volume. Theoretically, a gas cooled to −273° C. would lose $\frac{273}{273}$, or *all* its volume. At *zero* volume molecular motion would cease and the body would be without heat, or *absolutely* cold. For this reason, −273° C. is considered zero on the *absolute temperature scale.* The Absolute scale is never used for measuring temperatures. It is merely an arbitrary scale devised to eliminate the *zero* and the *minus* from the regular thermometer scales.

In reality all gases liquefy before absolute zero is reached. By evaporating liquid helium, Kamerlingh Onnes, at the University of Leyden, Holland, succeeded in getting the extremely low temperature of −272.2° C., within one degree of absolute zero. The relation between the Absolute scale and the Centigrade scale is shown in the following table:

C.	A.	V.
100°	373°	373 c.c.
50°	323°	323 c.c.
0°	273°	273 c.c.
−100°	173°	173 c.c.
−273°	0°	0 c.c.

By comparing columns one and two we see that the absolute temperature is exactly 273 degrees higher than the Centigrade temperature. Hence, to change from Centigrade to Absolute scale, we add 273 degrees to the Centigrade reading. The third column shows how 273 c.c. of gas at standard temperature, 0° C., would behave if subjected to the temperatures shown in the other columns. At 100° C., or 373° A., its volume is 373 c.c.; at −100° C., or 173° A., its volume is 173 c.c. From these observations, it is apparent that the LAW OF CHARLES may be stated as follows: *If the pressure be constant, the volume of a given mass of dry gas is directly proportional to the absolute temperature.*

PROBLEM. At a temperature of −23° C., the volume of a gas measures 1000 c.c. Find its volume at a temperature of 27° C.

Solution. −23° C. = 250° A., and 27° C. = 300° A. The gas has been warmed; hence it will expand to $\frac{300}{250}$ of its former volume. $\frac{300}{250} \times 1000 = 1200$ c.c., the new volume.

236. Law of Charles Shown Graphically. Let us use the absolute temperatures and volumes given in § 235 as coordinates in plotting a curve. The curve obtained is shown in Fig. 304. It is a simple direct proportion curve, and it shows graphically that the volume of a gas is directly proportional to the *absolute* temperature.

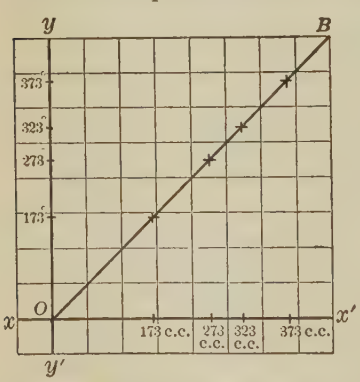


FIG. 304. — Curve to represent law of Charles.

If we plot a curve by using the volumes as abscissas and the *Centigrade* temperatures as ordinates, as shown in the above table, we see that the volumes are *not* proportional to the Centigrade temperatures at all. If we produce the curve

AB until it intersects the YY' axis at Z, we find that this point of intersection corresponds to $-273°$ C., or to zero degrees Absolute. This furnishes us with a graphic illustration of the *theoretical* temperature at which all gases cease to have volume. In the similar triangles, ZCD and ZOA, the volumes, as represented by OA and CD, are proportional to the *absolute* temperatures, OZ and CZ.

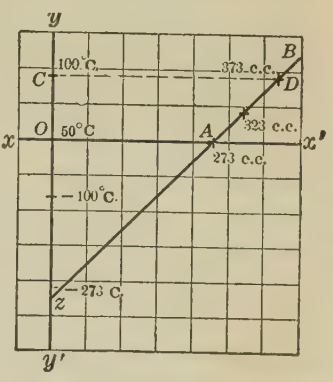


FIG. 305.— Curve to show absolute zero.

There is no simple volume relationship corresponding to 0° C. and 10° C., or to $-10°$ C. and 10° C. The latter two, if used in proportion, would give a negative volume, which is impossible. The Absolute scale eliminates the zero and negative temperatures of the Centigrade scale.

Absolute temperature, T, = Centigrade temperature, t, $+273$. Or, $T = t + 273$.

237. Problems Involving the Use of the Law of Charles. Given 400 c.c. of gas measured at 10° C.; suppose we wish to find what volume the gas will occupy at 60° C. We must first reduce the Centigrade temperatures to absolute. 10° C. $=283°$ A., and 60° C. $=333°$ A. Let V represent the original volume; V', the new volume; T, the original temperature; and T', the new temperature.

Then by the law of Charles, $V : V' = T : T'$.

Substituting, $400 : x = 283 : 333$.

Whence, $x = 470.6$ c.c.

It is quite as simple to solve by fractions. The temperature has increased and the volume will be correspondingly increased. Hence the new volume is $\frac{333}{283}$ of the original volume. $\frac{333}{283} \times 400 = 470.6$ c.c.

238. Problems Involving the Use of the Laws of Boyle and Charles. It frequently happens that both the temperature and pressure to which a given volume of gas is subjected may change. To find the new volume in such a case, we must use the laws of Charles and Boyle. We may find the effect of the pressure on the volume and then use this new volume in order to find the effect of temperature. Or we may find the effect of both by the use of a single statement.

PROBLEM. Given 500 c.c. of gas at 20° C. and 750 mm. pressure; find what volume the gas will occupy at 30° C. and 760 mm. pressure.

Solution. 20° C. = 293° A.; 30° C. = 303° A.

Then, $500 \times \frac{303}{293}$ = the volume corrected for temperature change only.

And, $500 \times \frac{750}{760}$ = the volume corrected for pressure change only.

Since both the temperature change and the pressure change occur simultaneously, we may combine the equations as follows:

$$500 \times \frac{303}{293} \times \frac{750}{760} = \text{corrected volume.}$$

NOTE. The increase in temperature from 20° C. to 30° C. causes the gas to expand by $\frac{303}{293}$ of its volume, and the increase in pressure reduces the volume by $\frac{750}{760}$.

The following formula may be used for solving problems when both the temperature and pressure change: $\frac{PV}{T} = \frac{P'V'}{T'}$. In this formula, P, V, and T represent the original pressure, volume, and temperature respectively; P', V', and T' represent the new pressure, volume, and temperature.

239. Force of Expansion. The force of expansion or contraction is enormous. Broken wires in winter, cracks in pavements, and the bursting of tires when highly heated all testify to the great force exerted by a change in temperature. The magnitude of this force seems to be limited only by the breaking strength of the material at the given temperature. With a steel bar of 1 sq. in. cross-sectional area, the force may be nearly 70 tons.

SUMMARY

In general, solids expand when heated and contract when cooled. The increase per unit length per unit degree is called the coefficient of linear expansion. The increase in area, or the coefficient of superficial expansion, is approximately twice the linear coefficient. The increase in volume, or the coefficient of cubical expansion, is three times the linear coefficient.

Liquids have a much higher coefficient of expansion than solids; alcohol expands nearly 30 times as much as steel, and mercury nearly 5 times as much. Water has its maximum density at 4° C.; heated above this temperature or cooled below it, water expands.

The coefficient of expansion of all gases is the same, 0.003665 per degree Centigrade.

A change in temperature or a change in pressure will change the volume of a gas. The GAS LAW, $\frac{VP}{T} = \frac{V'P'}{T'}$, is used to calculate the effect of temperature and pressure changes upon gas volumes.

QUESTIONS

1. How would thermometer readings be affected if mercury and glass had the same coefficient of expansion?

2. When two tumblers stick together they may usually be loosened by pouring cold water into the inner one, or by letting hot water run over the outer one. Explain.

3. Why must all the water in a pond be cooled to 4° C. before any of it freezes?

4. Why do ponds and lakes freeze around the edges before they do in the middle?

5. Fused silica has a coefficient of expansion of about 0.0000005. Explain why it is superior to glass for laboratory apparatus that is to be heated.

6. Why is a thin glass tumbler less apt to break when boiling water is poured over it than one made of thick glass?

7. A football is pumped up in a warm room. It is used out-of-doors on a cold day. Will it grow looser or tighter? Explain.

8. Why is invar used in making the tapes used by surveyors?

9. The coefficient of linear expansion of pyrex glass is about one third that of ordinary glass. Why is it suitable for baking dishes?

10. Would you expect to find high or low temperatures associated with high barometer areas? Explain.

11. Why are rivets and iron bolts heated red hot before they are put in bridges and steel plates?

12. Explain how the baking of bread is an application of the law of Charles.

13. When concrete roads are built, they are marked off in rectangular blocks. The cracks between the blocks are filled with tar. Explain.

14. Would a single large sheet of copper be satisfactory to cover one half of the roof of a house? Give a reason for your answer.

15. Metal straps are used to suspend steam-pipes from the basement ceiling. Explain why this method is used.

16. Upon a certain hot summer's day one of the drawbridges across the Passaic River could not be closed. Explain, and tell what method you would have used to close the drawbridge.

17. Why is it impossible to seal a brass wire into a glass rod?

18. Would you get more gas per cubic foot with a meter installed in the basement or in the attic?

19. How would natural conditions be affected if water continued to contract until it freezes?

20. Why does a small rubber balloon filled with hot air rise?

21. Why does the air that escapes from the valve of a pneumatic tire feel cool, even in hot weather?

22. Glass stoppers are sometimes hard to remove from bottles. They can generally be loosened by pouring hot water over the neck of the bottle. Explain.

PROBLEMS

1. An iron steam pipe is 30 ft. long at 20° C. What will be its length when steam is passing through it?

2. An aluminum wire is 1000 ft. long at 10° C. Find its length at 50° C.

3. A wire is 100 cm. long at 20° C. At 80° C., it is 100.1104 cm. long. What is its coefficient of linear expansion?

4. The steel cables of the Brooklyn Bridge are 5280 ft. long when the temperature is $-20°$ C. What will be their length at 35° C.?

5. Steel rails that are laid when the temperature is 20° C. measure 34 ft. If the maximum temperature is 122° F., how much space should be left between the rails?

6. A surveyor's tape made of invar is 100 ft. long when the temperature is zero degrees Centigrade. With this tape the surveyor measures a plot 3000 ft. long when the temperature is 86° F. How much will his measurement be in error?

7. A brass rod is 60 ft. long at 0° C. To what temperature must it be heated to increase its length by 0.324 ft.?

8. A man buys 100 gallons of alcohol when the temperature is 0° C. How many gallons will there be when the temperature rises to 20° C.?

9. A 1000-gallon tank is filled with petroleum when the temperature is 10° C. How much will over-flow if the temperature rises to 25° C.?

10. Given 900 c.c. of gas measured at 18° C. and 745 mm. pressure. Find what volume it will occupy when measured at 25° C. and 770 mm. pressure.

11. A gas measures 1200 c.c. at a temperature of 17° C. and a pressure of 800 mm. Find its volume at standard conditions of temperature and pressure.

12. A gas measures 400 c.c. at a temperature of 25° C. and a pressure of 800 mm. To what temperature must the gas be cooled if its volume is reduced to 350 c.c. when the pressure is 760 mm.?

13. A tire is inflated to a pressure of 40 lb. per sq. in. when the temperature is 5° C. Find the pressure of the air in the tire when the temperature rises to 25° C.

14. A room is heated from 0° C. to 20° C. What fractional part of the air escapes? If the density of the air at 0° C. was 0.00128 gm. per c. c., what will its density be at 20° C.?

15. A tire holds 600 cu. in. of air at a gauge pressure of 73.5 lb. per sq. in. The temperature is $-10°$ C. What volume will this air occupy at a temperature of 20° C. and under a pressure of one atmosphere?

CHAPTER 11

HEAT UNITS—CHANGE OF STATE

A. HEAT UNITS. SPECIFIC HEAT

Vocabulary

Dietetics, hygienic science relating to diet.
Fusion, melting.
Vaporization, changing from a liquid to a vapor.
Sublimation, changing from a solid to a vapor without melting.
Sulphur dioxide, a gas formed by burning sulphur.

240. Heat Units. We have learned that thermometers are used to measure *temperature.* We know, too, that two substances may have the same temperature, but different quantities of heat. When a man buys coal, he is interested to know how much *heat* he has bought, and not how high a temperature the coal will produce. We may measure temperature by the use of a thermometer, but in the laboratory we can measure the heat content of a weighed sample of coal by finding the effect it will produce. If we find, for example, that one sample will warm a liter of water one degree, and another sample of equal weight will warm twice as much water one degree, we know that the heat content of the latter is just double that of the former. We can also find the effect it will produce by determining the number of grams of ice one gram of the coal can melt.

In the Metric system, the heat unit used is the *calorie.* It may be defined as the *quantity of heat required to raise the temperature of 1 gram of water 1° C.* When one gram of water cools through one degree Centigrade, it *loses* 1 calorie of heat. One gram of a good soft coal gives out about 8000 calories

of heat when it burns. In dietetics the *large Calorie* is used; it is equal to 1000 small calories. When we say "A thick slice of bread furnishes 100 Calories," we mean that the bread, if totally oxidized, would supply the body with enough heat to raise the temperature of 1000 gm., or 1 Kgm., of water 100° C. Or, it would raise the temperature of 100 Kgm. of water 1° C. The Calorie measures the fuel value of the food.

In the English system, the heat unit used is the *British Thermal Unit* (*B.T.U.*, or *Btu*), which is the *amount of heat required to raise the temperature of 1 lb. of water 1° F.* One pound of water loses 1 B.T.U. in cooling 1° F. One pound of coal furnishes from 9000 to 16,000 *B.T.U.* One cu. ft. of fuel gas usually furnishes from 500 to 625 British Thermal Units. *One B.T.U. equals 252 calories.*

241. Heat Capacity. Some substances heat slowly and cool slowly. They absorb more heat units while they are being warmed, and liberate more heat upon cooling. The English scientist, Tyndall, devised the following experiment to show how heat capacities vary.

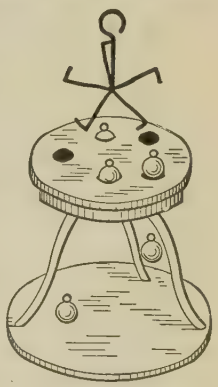


Fig. 306. — Heat capacity varies.

We have given five metal balls, aluminum, iron, copper, zinc, and lead. They are all heated to the same temperature, say 100° C., and placed upon a thin paraffin plate. (See Fig. 306.) The aluminum melts its way through the paraffin most rapidly, followed by the iron. The copper and the zinc follow at about the same rate, while the lead melts the paraffin slowly. The aluminum had absorbed more heat; hence it loses more heat to the paraffin. The lead has a very low capacity for absorbing heat, and melts paraffin slowly. The rate of melting in each case depends upon the heat capacity

of the metal. *The heat capacity of a body may be defined as the amount of heat required to raise its temperature 1° C.*

242. Specific Heat. Water heats slowly and cools slowly. It has a high heat capacity. From the definition of the calorie, we see that the *heat capacity of water is unity.* The specific heat of a substance is the ratio of its heat capacity to that of water.

In terms of the heat units, *the specific heat of a substance is the number of calories required to raise the temperature of 1 gm. of that substance 1° C.* In the English system, it is the number of B.T.U.'s required to raise the temperature of 1 lb. of that substance 1° F. Since it takes 1 calorie to raise the temperature of 1 gm. of water 1° C., and only 0.113 calorie to raise the temperature of 1 gm. of iron 1° C., the specific heat of iron is 0.113. A certain weight of iron when heated rises in temperature about 9 times as fast as the same weight of water, since its specific heat is only about $\frac{1}{9}$ as much as that of water. From Table 6, Appendix C, it may be seen that the specific heat of most substances is quite low compared to that of water.

Numerically, 1 calorie warms 1 gm. of water 1° C.; 100 calories warm 1 gm. of water 100° C.; and 100 calories will warm 100 gm. of water 1° C. In all these cases, if the substance does not melt or vaporize, *its weight in grams times its change in temperature in Centigrade degrees times its specific heat equals calories.* Or, *weight in pounds times change in temperature in degrees Fahrenheit times specific heat equals British Thermal Units.*

To illustrate: we find the number of calories needed to raise the temperature of 300 gm. of iron through 50° C. by multiplying its weight (300 gm.) by its change in temperature (50° C.) by its specific heat (0.113). Or, suppose we wish to find the number of calories 200 gm. of water will liberate in cooling from 80° C. to 20° C. Calories = weight (200 gm.) × temperature change (80° C. − 20° C.) × specific heat (1).

243. The Law of Heat Exchange. If we pour cold water into hot coffee, the water is warmed, and the coffee is cooled. The final temperature of the mixture will be some point between the two initial temperatures. If we touch a hot metal pan, the hand *gains heat.* If we touch a piece of ice, the hand *loses heat* to the ice. Whenever we bring into contact two substances of unequal temperature, or mix them, the warmer always loses heat, and the cooler gains heat until both have the same temperature. Prevost showed that *the total number of heat units lost by the warmer substance equals the number of heat units gained by the cooler substance.* This statement, known as the LAW OF HEAT EXCHANGE, is very useful in solving problems involving an exchange of heat.

For example, we may add 100 gm. of iron at 80° C. to 113 gm. of water at 25° C. When a constant temperature has been reached, both have a temperature of 30° C. Writing the temperatures one above another, as in Fig. 307, we see that the iron has cooled from 80° C. to 30° C., a change of temperature of 50° C. The water has been warmed from 25° C. to 30° C., a change of temperature of 5° C. But 100 gm. (wt. of iron) $\times$ 50 (temperature change) $\times$ 0.113 (sp. ht.) = 565 calories lost by iron. And, 113 gm. (wt. of water) $\times$ 5 (temperature change) $\times$ 1 (sp. ht.) = 565 calories, gained by the water. If any one of the six quantities is unknown, it can be found from the equation, *calories lost = calories gained.*

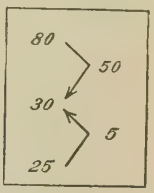


FIG. 307. — Both substances reach the final temperature.

244. Method of Finding Specific Heat. If the specific heat of the iron in the preceding section had been unknown, we could have determined it by finding experimentally the initial temperatures of the iron and the water, the weights of both, and the final temperature of both. Then we could have calculated the unknown quantity, or the specific heat of the iron. The method of mixtures is generally used for finding

specific heat. Suppose we have a lump of brass of which we wish to find the specific heat. A calorimeter, or metal cup, of known specific heat is weighed. Then it is filled about $\frac{2}{3}$ full of water and again weighed. The difference is the weight of water used. Next we weigh the lump of brass and suspend it in the steam arising from boiling water until its temperature is 100° C. The temperature of the water in the calorimeter is accurately measured, and the brass quickly introduced. (See Fig. 308.) The water is stirred with the thermometer until the mercury stops rising, and the final temperature is then read. The brass has cooled to the final temperature, and the water and the calorimeter have been warmed to the final temperature. Let us assume the following data:

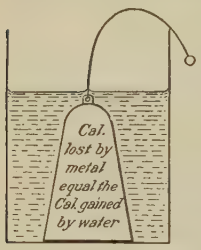


FIG. 308. — Metal loses heat to the water.

Weight of calorimeter	110 gm.
Specific heat of calorimeter	0.09
Weight of water	405 gm.
Weight of brass	201.9 gm.
Initial temperature of the water	20° C.
Initial temperature of brass	100° C.
Final temperature of water and brass	23.5° C.

The brass loses heat as follows:

Weight (gm.) × change of temperature × specific heat = calories.

Or, $201.9 \times (100-23.5) \times x$ = calories.

The water and the calorimeter gain heat as follows:

$110 \times (23.5-20) \times 0.09 = 34.65$ calories, gained by calorimeter.

$405 \times (23.5-20) \times 1.00 = 1417.5$ calories, gained by water.

Total calories gained = 1452.2.

By Prevost's theory, *heat lost equals heat gained.*

Then, $201.9(76.5)\ x = 1452.2$ calories.

Whence, $x = 0.094$, the specific heat of brass.

This method is a general one. In all problems involving heat exchange and specific heat, the student needs to con-

sider *which substances lose heat and which gain heat;* he should bear in mind the fact *that calories gained equal calories lost;* and he must remember *that weight in grams times change in temperature in degrees Centigrade times specific heat equals calories.*

245. Effects Produced by High Specific Heat of Water. In early June the air in the latitude of New York may seem quite warm. If we are rash enough to take a dip in some lake, we find the water decidedly cold. The water warms much more slowly than the land. In October the reverse is true. The air may be chilly, but the water will feel quite warm. Water cools slowly. It takes quite a long time to heat a quart of water to its boiling point. In a hot water bottle in the sick room a couple of quarts of water will remain warm almost all night.

Cities situated on large bodies of water are not subject to so great extremes of temperature, nor to such sudden changes of temperature as inland cities, unless the cities are affected by prevailing winds from the land. San Francisco has a more equable climate than St. Louis or New York.

B. FUSION

246. Fusion. When a solid is warmed, it absorbs heat. At a certain temperature, it changes from the solid to the liquid state. *The process of changing from the solid to the liquid state is called fusion, melting, or liquefaction.* The opposite process is known as *solidification.* The temperature at which such change occurs is called the *melting point.* The temperature at which a *crystalline* solid melts is usually the same as the temperature at which solidification or freezing occurs. Pure substances generally have a *definite* melting point. In fact the determination of the melting point is often used as a test for purity, since the presence of a small amount of impurity often changes the melting point decidedly.

Non-crystalline substances like glass and sealing wax have

no definite melting point, but they soften gradually when heated. Such substances may be heated until they soften and then be bent, molded, or welded. Wrought iron becomes plastic when it is heated. The blacksmith heats two pieces of wrought iron until they begin to soften, and then pounds them together into one piece. Such plastics as clay, glass, bakelite, celluloid, etc., find extensive industrial use. Cast iron has a sharp melting point; hence it cannot be welded. The tensile strength of a substance is reduced as its temperature rises. Structural material, such as steel, frequently collapses during fires as a result of such weakening, even before the melting point is reached.

247. Change of Volume on Solidification. If we pour molten paraffin into a tumbler and let it solidify, the center will be much depressed, showing that paraffin contracts during solidification. Most metals and alloys behave in the same manner.

When water solidifies, the reverse is true. Water pitchers are often broken by the expansion of water as it freezes. A pan half full of water shows a bulging, convex surface when the water freezes. (See Fig. 309.) The force of expansion is enormous; rocks are often broken by water collecting in crevices and expanding when it freezes. Water pipes often burst when the water freezes. The volume occupied by the ice is about 1.1 times that of the water from which it was formed. The erroneous idea that water pipes burst when they are thawed out is quite common. The pipes burst when the water freezes, but the leakage does not begin until the ice is melted. Bismuth and antimony also expand upon solidification. Antimony is a constituent of type-metal. Since it expands when the melted metal solidifies in the mold, it makes the type clear-cut.

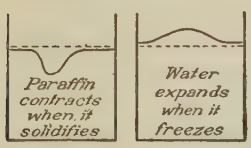


FIG. 309. — Some liquids expand upon freezing; others contract.

248. Why Change of Volume When Water Freezes Is Important. If water continued to contract when cooled below 4° C. and did not expand upon freezing, the density of ice would be greater than that of water. The first layer of ice formed would sink. Each successive layer would also sink as soon as formed until the entire body of water would be frozen solid.

The Great Lakes, as well as other lakes and rivers in the middle latitudes would eventually be closed to navigation. They would not thaw out even in summer, for the sun's rays do not penetrate water to any considerable depth. Fish and other forms of aquatic life would perish in the streams and lakes of the Temperate Zones.

249. Effect of Pressure on the Melting Point. When we make a snowball, some of the snow melts when we apply pressure to it. A substance that expands upon freezing has its melting point lowered by an increase in pressure. When the pressure is removed, the liquid freezes again. When we stop squeezing the snowball, the layer of water formed at its surface immediately freezes again. Such *melting under pressure and freezing again when the pressure is released is called regelation.* A very great pressure is required to change the melting point decidedly; a pressure of one atmosphere lowers the melting point of ice only 0.0075° C. If snow is much colder than its melting point, it will not "pack" readily. If we suspend two weights by means of a wire over a block of ice, as in Fig. 310, the pressure causes the ice directly beneath the wire to melt. Thus the wire gradually cuts its way through the ice and the water above it freezes again after

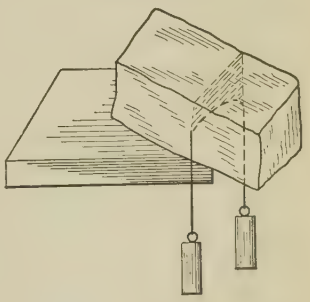


Fig. 310. — Pressure lowers melting point.

the pressure is released. Regelation plays an important part in the movement of valley glaciers.

If we increase the pressure on a substance such as paraffin, which contracts when it solidifies, its melting point is increased. The student will note that the behavior of such substances is just the opposite to that of substances which expand when they freeze. Some rocks in the interior of the earth are probably hot enough to melt at normal pressure, but they remain solid because they are under stupendous pressure. If the pressure is released, they melt and form the lava of volcanoes.

250. Heat of Fusion. If a pan of ice water containing a few lumps of ice is constantly stirred with a thermometer while it is being heated, the temperature of the mixture will not rise above 0° C. until all the ice is melted. Heat is certainly being absorbed, but since the temperature does not increase, it is evident that the heat is used only in *melting* the ice. *The number of calories required to melt one gram of a substance without increasing its temperature is called its heat of fusion.* Since the thermometer does not show any evidence of heat transfer, heat of fusion is sometimes called *latent* (hidden) heat. Careful experiments show that it requires 80 calories of heat to convert 1 gm. of ice at 0° C. into water at 0° C.; it requires 144 B.T.U. to change one pound of ice at 32 °F. into water at 32° F. Due to its very high heat of fusion, ice makes an excellent refrigerating agent. In melting, ice takes heat from the surrounding substances, thus lowering their temperature.

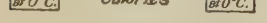


FIG. 311. — Heat of fusion.

In the heat of fusion we have an example of the effect of heat in producing a *change of state.* The result may be expressed by Fig. 311. If we subtract 80 calories of heat from 1 gm. of ice water, 1 gm. of ice at the same temperature will be formed.

251. Determination of Heat of Fusion. To find the number of calories needed to melt one gram of a solid, we use the

method of mixtures. We know that hot water will melt ice, for example, and we can find how many grams of ice can be melted by a known weight of water at a known temperature. We need the following data: weight of calorimeter; weight of water; weight of ice; initial temperature of hot water; and the final temperature when all the ice is melted.

PROBLEM. A calorimeter weighing 100 gm. has a sp. ht. of 0.09; it contains 400 gm. of water at 40° C.; 91 gm. of dry ice are introduced. When the ice is all melted the temperature is 18.2° C. What is the heat of fusion of the ice?

Solution. Both calorimeter and water lose heat as follows:

$100 \times (40 - 18.2) \times 0.09 = 196.2$ calories (lost by calorimeter).

$400 \times (40 - 18.2) \times 1.00 = 8720$ calories (lost by water).

Total calories lost $= 8916.2$

These 8916.2 calories did two things: first, they melted 91 gm. of ice; second, they raised the 91 gm. of water thus formed from 0° C. to 18.2° C.

$91 \times (18.2 - 0) \times 1.00 = 1656.2$ calories gained by water.

$8916.2 - 1656.2 = 7260$ calories, which were used to melt the ice.

$7260 \div 91 = 79.8$ calories used to melt one gram of ice, or its heat of fusion.

SUGGESTION. The student will do well to remember that one gram of ice water is formed for every gram of ice that melts. As this ice water is being warmed to the final temperature, it takes part of the heat from the hot water.

252. Heat Set Free When Water Freezes. We have learned that heat must be added to a solid to melt it. When a liquid solidifies or freezes, it seems natural to expect that heat will be liberated, because energy is indestructible. As a matter of fact, when one gram of water at 0° C. freezes, it sets free 80 calories of heat to the surrounding medium. The air in winter is warmed by the heat liberated during the formation of snow and ice. For this reason the weather often moderates just before or during a snowstorm. Tubs of water in cellars may give off enough heat upon freezing to protect canned fruits and vegetables from freezing.

253. Heat Absorbed in Solution. Dissolving salt in water lowers the temperature. A still more decided lowering of the temperature occurs when sal ammoniac, potassium iodide, or ammonium sulphocyanide is dissolved. Some of the heat energy of the solvent is used in dissolving the solute. Because heat energy breaks down the solid, heating the solvent not only causes a substance to dissolve more rapidly, but in almost all cases it increases the total quantity that can be dissolved.

254. Freezing Mixtures. We cannot make ice-cream or frozen puddings by the use of ice alone. The melting point of the ice is approximately the same as that of the substance to be frozen. When salt is put on ice it dissolves in the surface moisture. But a solution of salt in water freezes at a lower temperature than pure water. In fact the freezing point of a saturated solution of salt in water is $-22°$ C. Since the salt solution has a lower melting point than water, salt added to ice makes the ice melt rapidly. Both the melting of the ice and the dissolving of the salt absorb heat. Taking heat from the cream or the pudding lowers its temperature. If we continue to take heat away from a liquid, it will eventually be cooled below its freezing point.

QUESTIONS

1. Why does snow "pack"? Why is it impossible to make snowballs if the temperature is much below 32° F.?

2. Why is the climate along the southern shores of Lakes Erie and Ontario suitable for fruit-growing?

3. Which cools a refrigerator more, 1 lb. of ice or 1 lb. of ice-water? Explain.

4. Explain how regelation helps in the movement of valley glaciers.

5. Which will keep warm longer in a sick room, a 7-lb. flat-iron, or 4 lb. of hot water, if both have the same original temperature?

6. Compare the climates of New York and Honolulu. How do you account for the difference?

PROBLEMS

1. A calorimeter weighs 110 gm. Its specific heat is 0.09. If its temperature is 10° C., how many gm. of water at 40° C. must be poured into it to raise its temperature to 26° C.?

2. A piece of iron weighing 200 gm. has a temperature of 200° C. It is put into 400 gm. of water which has a temperature of 20° C. If the temperature of the water rises to 29° C., what is the sp. ht. of the iron?

3. 300 gm. of metal at 98° C. are mixed with 526 gm. of water at 20° C. The temperature rises to 26° C. Find the sp. ht. of the metal.

4. How many B.T.U.'S will be needed to raise the temperature of 4 lb. of stone from 60° F. to 300° F., if the stone has a sp. ht. of 0.4?

5. How many calories of heat are needed to melt 140 gm. of ice? How many additional calories are required to raise the temperature of the water thus formed to 60° C.?

6. A calorimeter, sp. ht. 0.1, weighs 100 gm. It contains 100 gm. of water at 20° C. A platinum ball weighing 60 gm. is taken from a furnace and plunged into the water. The temperature of the water rises to 35° C. What was the temperature of the furnace?

7. 400 gm. of a substance at a temperature of 150° C. were placed upon a block of ice at 0° C. When the substance had cooled to zero, it was found to have melted 100 gm. of ice. What is its specific heat?

8. An aluminum container weighs 2 lb. Its temperature is 68° F. Two soapstone discs weighing 6 lb. each are heated to a temperature of 400° F. and then placed in the container. The discs have a sp. ht. of 0.2; the sp. ht. of aluminum is 0.2. A 5-lb. roast, having a sp. ht. of 0.5, is then placed in the container. If the original temperature of the roast was 68° F., find the maximum temperature to which it will be heated.

9. 200 gm. of metal having a temperature of 100° C. are plunged into 400 gm. of water at 20° C. The temperature rises to 28° C. What is the sp. ht. of the metal?

10. A glass tumbler has a sp. ht. of 0.2. It weighs 300 gm. and has a temperature of 60° C. A certain amount of ice was added to the tumbler. The ice was all melted and the final temperature was 10° C. How many gm. of ice were added?

11. 100 gm. of ice at 0° C. are stirred in 400 gm. of water at 60° C. Calculate the final temperature.

12. 100 gm. of ice, 400 gm. of ice water, and 1000 gm. of boiling water at 100° C. are all mixed. Calculate the final temperature.

C. VAPORIZATION. CONDENSATION

255. Vaporization. Just as the addition of heat to a solid changes it into a liquid, so a liquid may be changed into a gas or vapor by the addition of heat. The process of converting a liquid into a vapor is called *vaporization.* As the liquid is warmed, the more rapidly moving molecules escape from the surface. We call this process *evaporation.*

If we put a basin of water over a gas flame, bubbles of water vapor soon begin to form at the bottom of the basin. As these bubbles rise through the cooler layers of liquid above them, they collapse, causing the familiar "singing" so often noticed before liquids begin to boil. When the entire liquid is hot enough so that these bubbles reach the surface freely, vaporization takes place throughout the liquid with visible disturbance. Such vaporization is called *boiling* or *ebullition.*

256. Laws of Evaporation. Since molecules disappear from the liquid during evaporation, anything that causes the molecules to escape from the surface more rapidly will accelerate evaporation. The rate of evaporation must therefore depend upon several factors.

1. We know that heat causes the molecules to move more rapidly. The faster moving molecules escape more rapidly. Raising the temperature of the liquid increases molecular motion; therefore *the rate of evaporation increases with an increase of temperature.*

2. If we pour a quart of water from a deep, narrow vessel into a broad, shallow pan, we have increased the surface area decidedly. Common sense leads us to believe that more molecules can escape from an area of 100 sq. in. in a

certain time than from an area of 5 sq. in., and the facts justify our belief. Hence we conclude that *the rate of evaporation increases as the surface area of the liquid increases.*

3. Alcohol evaporates much faster than water; ether evaporates faster than alcohol; and some liquids evaporate still more rapidly than ether. *The rate of evaporation varies with the nature of the liquid.*

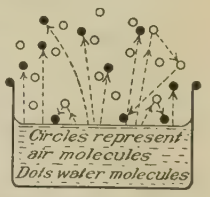


FIG. 312. — Air molecules retard evaporation.

4. Naturally the air molecules above the surface of the liquid retard evaporation. Some of the molecules that escape must collide with air molecules, and rebound to the liquid. (See Fig. 312.) If the air above the surface is removed, evaporation is accelerated. It is very rapid in a vacuum. *The rate of evaporation is increased when the atmospheric pressure is reduced.*

5. As water molecules escape from the surface, they occupy a part of the space between the air molecules. (See Fig. 313.) Then the water molecules will also collide with such molecules and rebound. When the number of molecules returning to the surface per second just equals the number escaping in the same time, the air is saturated. When the air is nearly saturated with vapor, water evaporates slowly. *The rate of evaporation increases as the relative humidity is reduced.*

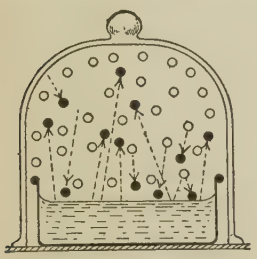


FIG. 313. — Saturated vapor.

6. Wet clothes dry very rapidly on a windy day. The saturated air in the immediate vicinity is removed by the wind and replaced by unsaturated air. Hence *the rate of evaporation increases with the rate of change of the air in contact with the liquid.*

257. Sublimation. The molecules of solids are also in motion, but much more slowly than those of liquids. Such solids as ice, camphor gum, iodine, musk, "moth balls," etc., disappear by evaporation. They may change directly from a solid to a vapor without melting. Such a process is called *sublimation.* Snow and ice disappear on cold winter days even when the temperature is below their melting point. At a temperature of 0° C., the vapor pressure of the molecules at the surface of ice is equal to 4.5 mm. of mercury. Solids that sublime readily may be purified by this process.

258. How Pressure Affects the Boiling Point. From an examination of the curve shown in Fig. 314, we see that the pressure which water vapor exerts increases very rapidly with an increase in temperature. To illustrate, the vapor pressure is 4.5 mm. at 0° C.; it rises to 17.3 mm. at 20° C.; at 80° C., it is 354.7 mm.; and at 100° C., its pressure is 760 mm. *A liquid boils when its vapor pressure equals the atmospheric pressure.* On a day when the barometer reads 760 mm., the *boiling point* of water is 100° C. If we increase the pressure to 787 mm., water must be heated to 101° C. before it will boil. On the other hand, water boils at 99° C., when the air pressure upon its surface is only

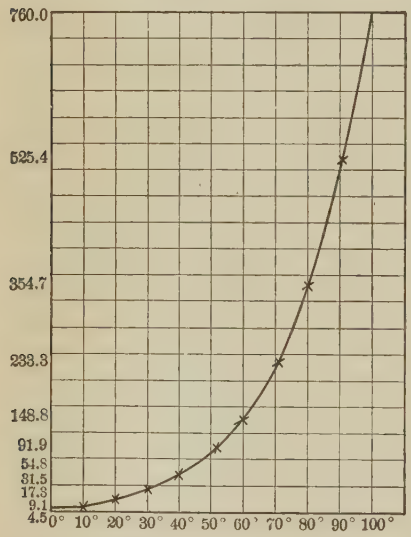


FIG. 314. — Boiling point varies with atmospheric pressure.

733 mm. Near the normal boiling point, a variation of 27 mm. in the atmospheric pressure causes the boiling point to vary 1° C.

259. Pressure Cooking. As we ascend a mountain, the air pressure becomes less, and the boiling point of water is also decreased. At a pressure of 525.4 mm., water boils at 90° C. This means that water will come to the boiling point quickly, but that it will not be very hot. In fact the boiling temperature is too low to cook vegetables and other foods by boiling in open vessels. It is difficult to hard-boil eggs at the altitude of Denver or Quito. At an elevation of 900 ft., the boiling point is lowered about 1° C.

At higher altitudes pressure cookers are used. (See Fig. 315.) The lid of such a cooker is clamped on tightly so that the steam cannot escape. The pressure inside is increased because the pressure of the saturated water vapor is *added* to that of the air pressure. In such a cooker the temperature may rise to 110° C. or even to 120° C. Foods cook about twice as fast at 110° C. as they do at 100° C., and about four times as fast as they do at 90° C. A pot roast can be cooked in about 40 minutes in a pressure cooker when the gauge pressure is 25 lb. per sq. in. Such cookers are also used at lower altitudes to save time. They are also used in canning vegetables, since the higher temperature produces more complete sterilization.

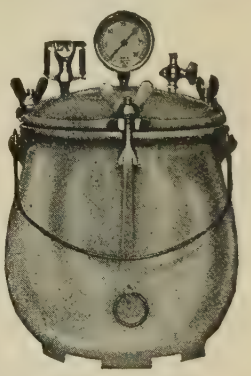


FIG. 315. — Denver pressure cooker.

260. Boiling at Reduced Pressures. Let us take a round-bottomed flask containing a little water and heat it until the water begins to boil. Then we remove the flame and stopper the flask tightly. When the flask is inverted, as shown in Fig. 316, a sponge with cold water applied to

the outside of the flask will cause the water inside to boil vigorously. The cold water condenses the steam and produces a partial vacuum inside. The water boils when the pressure is reduced. When the boiling stops, it may be started again by adding more cold water. Water can be made to boil at room temperature if we put it under a bell glass and exhaust the air. *Vacuum pans* are used to boil liquids at low temperatures. The syrup from which sugar crystals are obtained is evaporated in vacuum pans at a temperature low enough to prevent scorching.

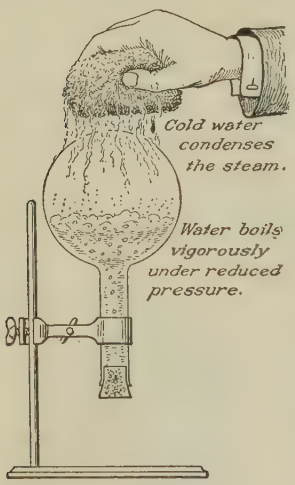


FIG. 316. — Lowering the pressure reduces the boiling point.

261. Laws of Boiling. Several facts concerning boiling liquids have been determined. We know that a liquid does not boil until the pressure of its saturated vapor equals the pressure upon the surface of the liquid. The temperature at which this condition occurs is called the *boiling point.*

1. The boiling point is sometimes used to identify liquids or to determine their purity. This is possible because *every pure liquid has a definite boiling point under the same conditions of pressure.*

2. A liquid does not get hotter as it continues to boil. Water boiling vigorously has the same temperature as water boiling slowly. Hence we conclude that *the boiling point of a pure liquid does not change, but it remains constant until all the liquid has vaporized.*

3. From what we learned in the preceding sections, we know that *the boiling point of a liquid rises as the atmospheric pressure increases, and falls as the pressure decreases.*

4. Solids or gases dissolved in liquids change the boiling point of the liquids. Salt water boils at a higher temperature than fresh water. In general, *solids dissolved in liquids raise the boiling point. Gases dissolved in liquids usually lower the boiling point.*

5. When two or more liquids having different boiling points are mixed, the mixture has a different boiling point. Generally its boiling point is some temperature between

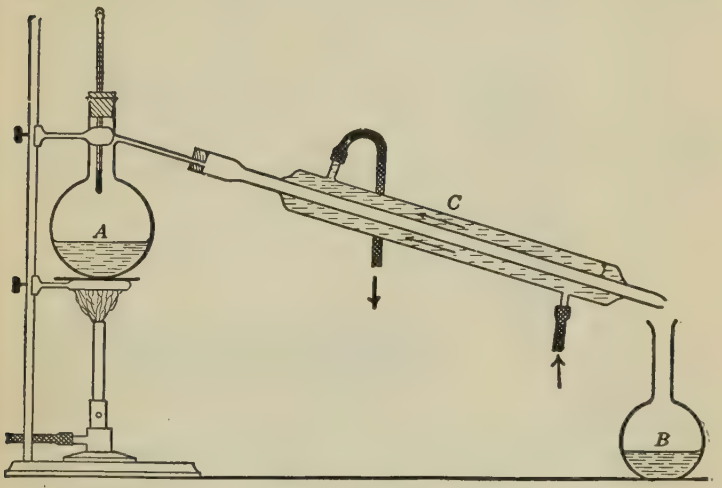


FIG. 317. — Distillation.

the boiling points of the pure liquids. For example, water boils at 100° C., and alcohol at 78° C. A mixture of the two will usually boil at some temperature between 78° C. and 100° C.

262. Distillation. Quite often it is desirable to obtain water that is free from mineral matter. Distilled water is used for storage batteries in automobiles and in radio sets. In distilling a liquid, we convert it into vapor and then condense the vapor. Any mineral matter which had been

dissolved in the liquid remains in the flask, unless the mineral matter is volatile.

The apparatus shown in Fig. 317 is much used in chemical laboratories for purifying liquids that contain non-volatile impurities. The liquid to be distilled is put in the flask *A* and heated to boiling. *C* is a double-walled condenser through which cold water circulates. The vapor condenses in the inner tube and runs down into the receiver at *B*.

263. Fractional Distillation. Many motorists fill the radiators of their cars in winter with a mixture of water and

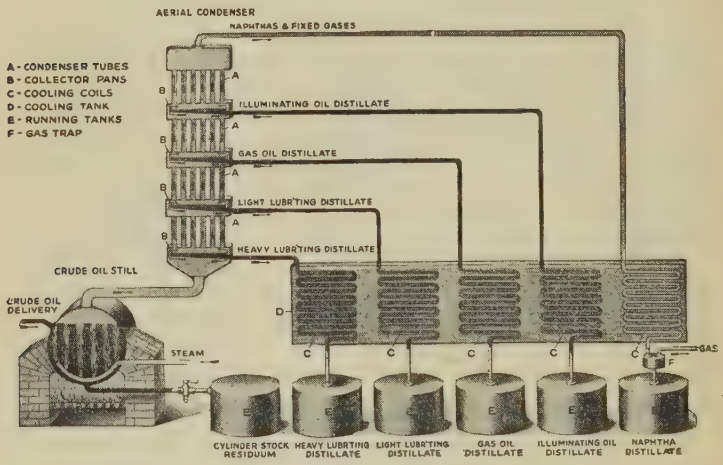


FIG. 318. — Fractional distillation of crude petroleum. (*Courtesy of Tidewater Oil Company.*)

denatured alcohol. The boiling point of the alcohol is about 80° C. Therefore when the motor gets warm much of the alcohol may boil off. Of course some of the water evaporates at the same time, but the mixture that is left contains a much smaller per cent of alcohol than before, and it will freeze more quickly than the original mixture. One fraction distils faster than the other.

Petroleum, or crude oil, is a mixture of a number of liquids that have different boiling points. Some of the most important of these substances are gasoline, kerosene, naphtha, lubricating oils, vaseline, and paraffin. When the mixture is heated, the products that have low boiling points boil off first, followed by those of higher boiling points. The process of separating the different products is called *fractional distillation.* Fig. 318 shows a still and fractionating column used to separate the products of different boiling points that are found in crude oil. Some complex solids, such as wood and coal, yield many products when they are *dry* distilled. The process is called *destructive distillation.*

264. Heat of Vaporization. If we put a quart of ice water on a gas stove, it may take about 5 minutes to heat it to the boiling point. Of course every gram of it has absorbed 100 calories, since it has been warmed 100° C. Suppose we continue to heat it until it has all boiled away. We find that it takes more than five times as long to evaporate it to dryness as it did to raise it to the boiling point. Of course it was absorbing heat all the time, but the heat served to change the water at 100° C. into vapor at the same temperature. We must conclude that it takes more than 500 calories to vaporize 1 gm. of water. *The heat required to vaporize 1 gm. of a substance without changing its temperature is called its heat of vaporization.*

Fig. 319. — Heat of vaporization.

By using the method of mixtures that was discussed under heat of fusion, it may be shown that it requires 536 calories of heat to vaporize 1 gm. of water, or to change it from water at 100° C. to steam at 100° C. (See Fig. 319.) Note that there is no temperature change. In the English system, the heat of vaporization of water is 965 B.T.U.'s per lb. To vaporize 1 gm. of alcohol, 205 calories per gm. are needed. To change 1 gm. of liquid

ammonia to gaseous ammonia, one must add 295 calories of heat. Later we shall see how this fact is utilized in making ice.

265. Method of Finding Heat of Vaporization. The method of mixtures is generally used to determine the heat of vaporization of a liquid. The calorimeter C, Fig. 320, is weighed and then filled two-thirds full of water. The weight of the water is determined and also its temperature. Steam from the boiler B is then introduced. The trap T collects the water from the steam that condenses before passing into the calorimeter. When a sufficient quantity of *dry* steam has been introduced, the tube is removed, the temperature observed, and another weighing taken. The increase in weight equals the weight of steam introduced. Suppose we obtain the following data:

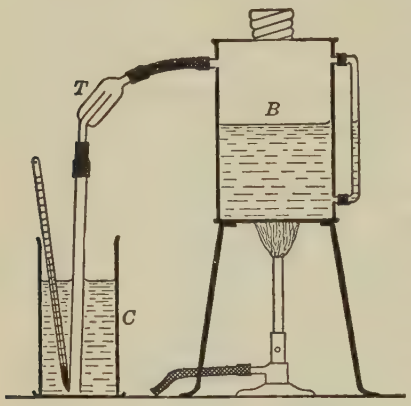


FIG. 320. — Heat of vaporization.

Weight of calorimeter	120 gm.
Specific heat of calorimeter	0.09
Weight of water	401 gm.
Weight of steam	23.5 gm.
Initial temperature of water	6° C.
Final temperature of water	40° C.
Temperature of steam	100° C.

Computations:

$120 \times (40 - 6) \times 0.09 = 367$ calories absorbed by calorimeter.

$401 \times (40 - 6) \times 1.00 = 13{,}634$ calories absorbed by water.

Total calories absorbed = 14,001.

When 23.5 gm. of steam condense, 23.5 gm. of water at 100° C. are formed.

$23.5 \times (100 - 40) \times 1.00 = 1410$ calories lost by water in cooling from 100° C. to 40° C.

$14{,}001 - 1410 = 12{,}591$ calories lost by 23.5 gm. of steam on condensing.

$12{,}591 \div 23.5 = 535.7$ calories, heat of vaporization.

266. Heat Given Out on Condensation. It is impossible to destroy energy. Hence if heat energy is absorbed in vaporizing a substance, it must be liberated again when the vapor of the substance condenses. This principle is much used in steam heating systems. In the boiler, water is being converted into steam. The steam expands and enters the radiators. As it condenses, every gram sets free 536 calories of heat.

Steam produces a much more severe burn than boiling water. The temperature of both may be exactly the same, but every gram of steam loses 536 calories when it condenses to water. Since it forms one gram of water at 100° C. when it condenses, it still has the same heating effect as the boiling water, although it has already set free 536 calories.

267. Cooling Effect of Evaporation. When one hand is wet, it soon feels colder than the other. It takes heat to change the water into vapor. Since this heat is taken from the hand, it produces a cooling effect. Alcohol used as a sponge bath may reduce fever. It evaporates faster than water, and cools the skin more rapidly. Ether boils at about 35° C. When poured on the hand, it evaporates so rapidly that the hand will feel cold.

If we put a few drops of water on a wooden block, place a watch glass containing a couple of teaspoonfuls of ether thereon, cover the whole with a bell glass, and exhaust the air from the bell glass very rapidly, the ether will boil under reduced pressure. The very rapid evaporation of the ether

takes heat from the small film of water under the watch glass so rapidly that the water freezes.

We sprinkle the streets in hot weather. The evaporation of the water takes heat from the pavements. The skin is a delicate thermostat. When we become too warm, the pores open and we perspire freely. The evaporation of the perspiration keeps us cool.

268. Artificial Ice. The manufacture of artificial ice depends upon the principle of cooling by evaporation. The faster the evaporation, the greater the cooling effect. By using am-

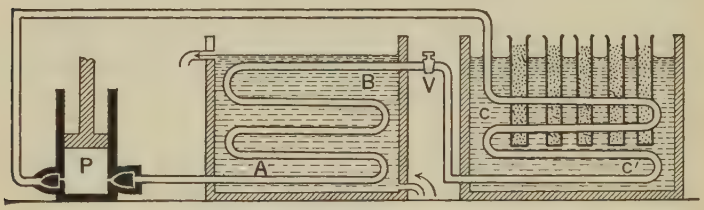


Fig. 321. — Diagram of an artificial ice plant.

monia, a liquid whose boiling point at atmospheric pressure is $-34°$ C., a very low temperature may be produced. At ordinary temperatures ammonia is a gas, but it may be easily liquefied by cooling and compression. Fig. 321 shows a diagram of a plant used to make artificial ice. The gas is compressed in the cylinder by the piston P, the heat of compression being absorbed by cold water. The liquid ammonia flows through the expansion valve V into the coils C and C', which are immersed in brine. As it evaporates, every gram of ammonia absorbs about 295 calories of heat from the brine, which is thus cooled below the freezing point of fresh water. Cans of fresh water immersed in the brine are frozen into cakes of solid ice in from 36 to 48 hours.

In cold storage plants the brine is pumped through pipes in the storage rooms. Just as hot water flowing through pipes in a room warms it by radiation, so the circula-

tion of the cold brine cools the room to any desired temperature.

269. Mechanical Refrigeration. In many homes and apartment houses either electricity or gas is used to produce ice

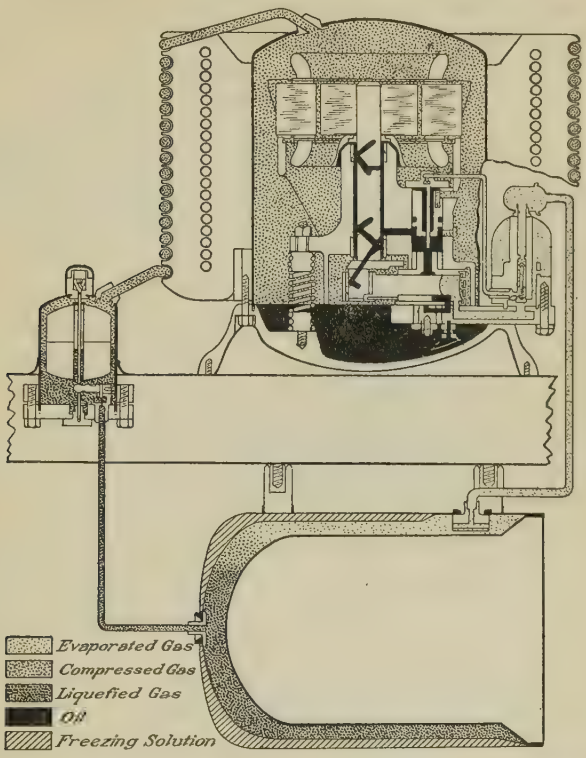


FIG. 322. — Circulation of sulphur dioxide through refrigerating coils and compressor.

or to keep refrigerators cool. In the electric refrigerator shown in Fig. 322 an electric motor is used to operate a small compressor. The gas used is sulphur dioxide. The heat produced when this gas is compressed is carried away by running water or by the circulation of the air. (See Fig. 323.)

Sulphur dioxide is easily liquefied when compressed. The liquid sulphur dioxide is led to the coils in one compartment of the refrigerator. As it evaporates in the coils, it absorbs heat from the surrounding air. Water placed in shallow pans in the center of the coils is converted into ice.

Michael Faraday liquefied chlorine gas by heating one end of a thick-walled glass tube containing chlorine while the other end of the tube was immersed in a freezing mixture. The compression and cooling caused the gas to liquefy. One type of refrigerator uses a similar principle. The heat from a gas flame is used to make ice. Water, ammonia, and hydrogen gas are placed in a series of pipes and sealed. The ammonia gas is very soluble in water, but it is driven out of its water solution by the heat of the gas flame. This rapid expulsion of the ammonia gas compresses it until it liquefies. The heat of compression is absorbed by water flowing around the pipes in which the compression occurs. Then the ammonia evaporates and expands in other coils, thus producing a cooling effect. It is redissolved in the water. The hydrogen prevents the formation of a vacuum by the rapid solution of the ammonia. The process is repeated continually. (See Fig. 324.)

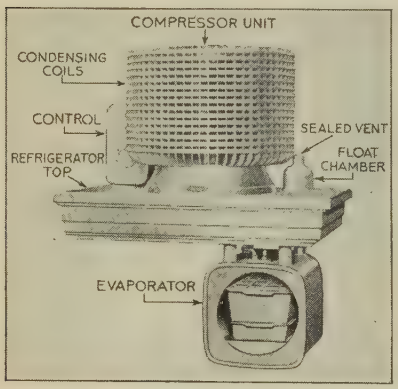


Fig. 323. — The heat of compression is carried away by the air. Ice forms in pans as the sulphur dioxide evaporates.

270. Liquefaction of Gases. Some gases cannot be liquefied by pressure alone. Air, for example, must be cooled to —140° C. before any pressure, however great, will cause it to become

liquid. The temperature to which a gas must be cooled before it can be liquefied by pressure alone is called its *critical temperature*. The pressure required to liquefy a gas at its critical temperature is called its *critical pressure*. By the use of high pressures and subsequent cooling by expansion, all gases have been liquefied. Successive compressions are

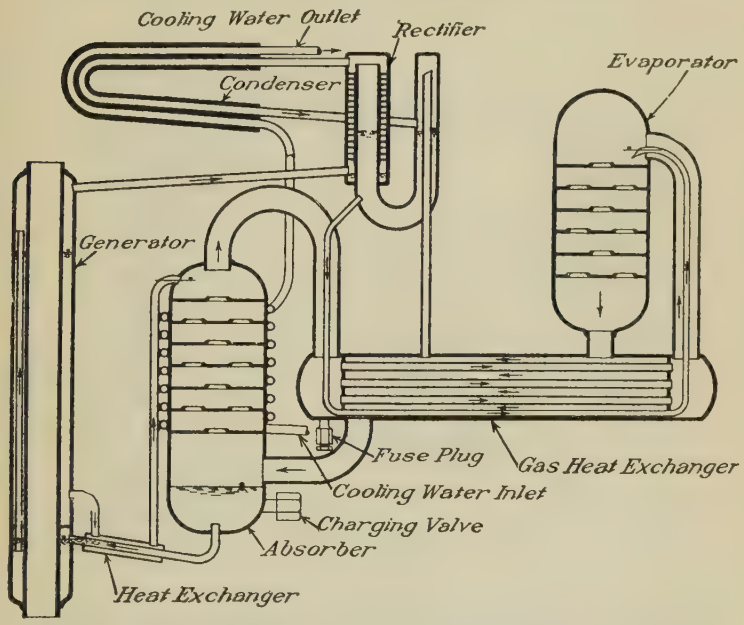


FIG. 324. — Heat compresses gas. Water cools it. The liquid formed evaporates and produces a cooling effect.

necessary in the case of gases that have a very low boiling point. In the apparatus shown in Fig. 325, air may be compressed, passed through the cooling coils to absorb the heat of compression, and then cooled by expansion as it passes through the valve *V*. It flows back through the outer of the two concentric coils to be compressed again. By such con-

tinual compression and cooling, some of the air is finally cooled to its critical temperature.

Liquid air under atmospheric pressure boils at from −182° C. to −194° C., the variation depending upon the per cent of nitrogen present. Liquid hydrogen boils at −253° C. If we throw a piece of ice into a vessel of liquid air, it will

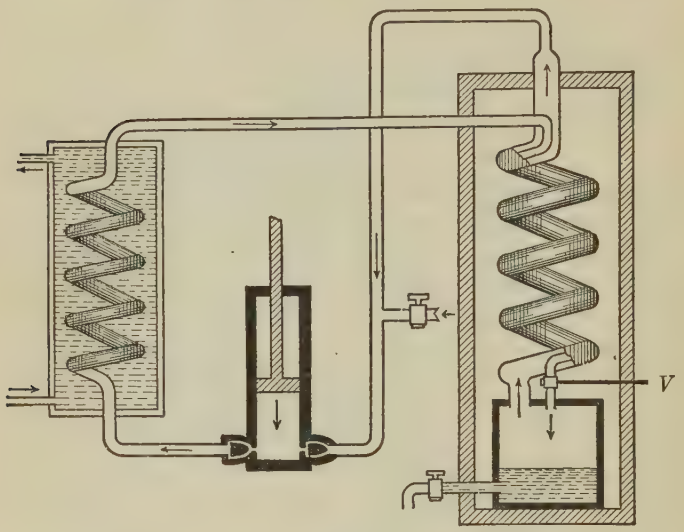


Fig. 325. — Linde's apparatus for liquefying air.

probably boil over. The ice is so hot compared to the liquid air that it makes it boil vigorously. Boiling water is only 100 Centigrade degrees hotter than ice, but ice is more than 180 Centigrade degrees hotter than liquid air. Carbon dioxide is not only now liquefied, but it is solidified and used to keep ice-cream from melting. It is known as "dry ice," since it sublimes without melting.

271. Effect of Heat on Water Shown Graphically. Suppose we plot a curve to show what changes take place when ice at −10° C. is heated until it is all converted into steam under

pressure at 120° C., using temperature changes as ordinates and heat units as abscissas. (See Fig. 326.) Since the specific heat of ice is 0.5, 1 gm. of ice absorbs 5 calories in being warmed to zero degrees; 80 calories are absorbed in melting the ice. *Note that there is no temperature change;* 100 additional calories are needed to warm the water to the boiling point. Another change of state occurs, in which 536 calories

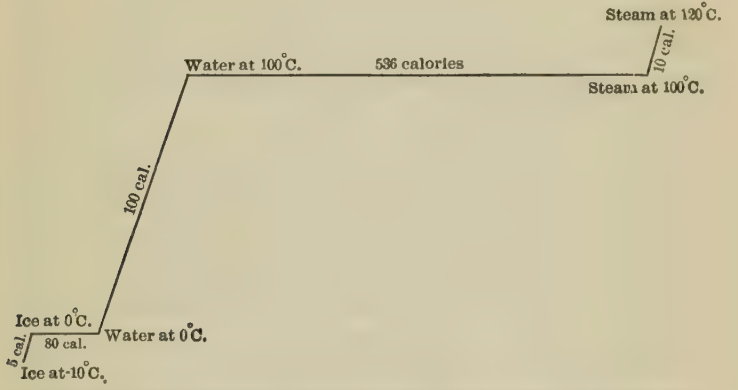


FIG. 326. — Heat absorbed during change of state and of temperature.

of heat are absorbed. If the steam, which has a specific heat of almost 0.5, is under pressure, 10 calories will be used to heat 1 gm. from 100° C. to 120° C. The student will find this curve helpful in solving problems involving specific heat, heat of fusion, and heat of vaporization. We see that it needs 716 calories of heat to change 1 gm. of ice at 0° C. into 1 gm. of steam at 100° C.

D. HUMIDITY

272. Humidity. At all times the air contains some water vapor. Evaporation is constantly taking place, even when the temperature is 32° F., or lower. The amount of moisture present in the air varies from time to time. The air near a

large body of water is apt to be more humid than the air near an inland city. Of course the winds carry the moisture to inland places when they blow shoreward.

273. Capacity. The amount of water vapor which the air *can* hold when it is saturated is its *capacity*. Capacity is usually expressed in grains per cu. ft. It varies greatly with the temperature. Table 5 in Appendix C shows that a cubic foot of warm air can hold much more water vapor than a cubic foot of cold air. From our study of the rate of evaporation, this is exactly what we would expect, because an increase in temperature increases the rate at which molecules escape from the surface of a liquid.

274. Absolute Humidity. Since collision with air molecules retards evaporation, the air is not always saturated. The amount of moisture which the air *does* contain is called its *absolute humidity*. We may illustrate the difference between capacity and absolute humidity by the following example. If we pour one pint of water into a quart bottle, the amount of liquid the bottle *does* contain is one pint; the capacity of the bottle, or what it could contain, is one quart.

275. Relative Humidity. When a quart bottle contains one pint of liquid, it is 50% full. If a cubic foot of air that *could* hold 4 grains of water vapor *does* hold only 2 grains, it is 50% full, or half-saturated. *The ratio of the amount of moisture which the air does contain to what it could contain is called its relative humidity.* We find relative humidity by dividing the absolute humidity by the capacity. It is usually expressed in per cent.

276. How Relative Humidity is Affected by the Temperature. A cold room often feels damp. When a fire is started in the room, it then feels dry. The increase in temperature increases the capacity, and thus lowers the relative humidity. To illustrate, suppose the air actually holds 2 grains of vapor per cu. ft. on a day when the temperature is 32° F. The capacity, as shown by the table, is 2.113 grains. The rela-

tive humidity equals $2 \div 2.113$, or 94%. The air under such conditions will feel very damp. If the temperature is raised to 68° F., the amount of moisture will remain the same, but the capacity is increased to 7.48 grains per cu. ft. The relative humidity now equals $2 \div 7.48$, or 26%. The air will now feel very dry. Hence *increasing the temperature decreases the relative humidity.*

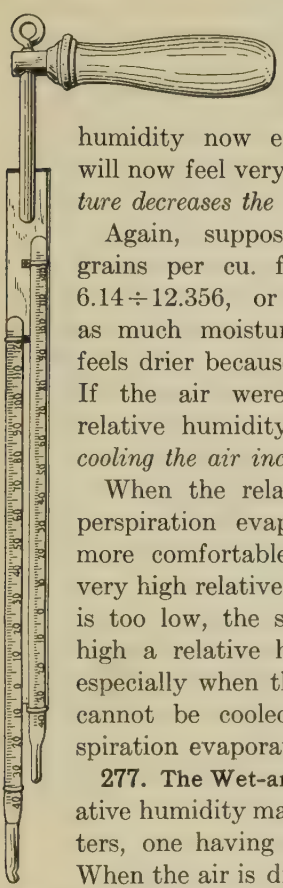


Fig. 327. — Sling psychrometer.

Again, suppose air at 84° F. contains 6.14 grains per cu. ft. The relative humidity equals $6.14 \div 12.356$, or 49%. The air has three times as much moisture as in the preceding case, but it feels drier because its *relative* humidity is fairly low. If the air were suddenly cooled to 62° F., the relative humidity would rise to 100%. Therefore, *cooling the air increases the relative humidity.*

When the relative humidity is below 50%, the perspiration evaporates quite rapidly and we feel more comfortable than at either a very low or a very high relative humidity. If the relative humidity is too low, the skin becomes dry and chafed. Too high a relative humidity is just as uncomfortable, especially when the temperature is high. The body cannot be cooled in hot weather unless the perspiration evaporates readily.

277. The Wet-and-Dry-Bulb Thermometers. The relative humidity may be found by using two thermometers, one having a dry bulb, the other a wet bulb. When the air is dry, the moisture evaporates rapidly from the wet bulb, lowering its temperature. (See Fig. 327.) The faster the evaporation, the greater the difference of temperature between the two thermometers. Tables have been constructed for showing the relative humidity directly from

the difference between the two thermometer readings. The hygrodeik, Fig. 328, is an application of the same principle. The curves are so plotted that relative humidity, dew point, and absolute humidity may all be read directly. (See Table 13 of Appendix C.)

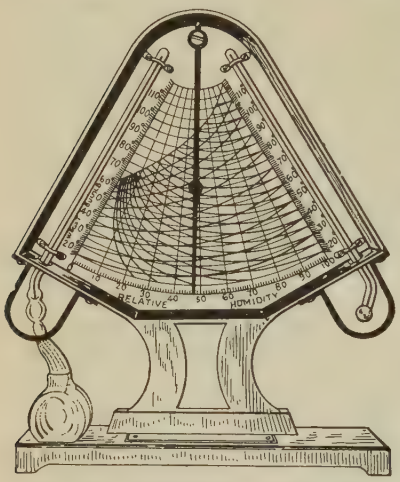


FIG. 328. — Hygrodeik. Dew point, absolute and relative humidity.

278. Precipitation. Since cooling the air increases the relative humidity, the air may be cooled until the relative humidity reaches 100%. Further cooling results in a condensation of some of the moisture. *The temperature at which the water vapor in the air begins to condense is called the dew point.* Before precipitation of any kind can occur, the air must be cooled below the dew point. If the air at 84° F. contains 8 grains of vapor, it will begin to lose moisture by condensation when it is cooled to 70° F., because the capacity of air at 70° F. is only 7.98 grains per cu. ft. If cooled to 60° F., every cu. ft. of air will lose about 2.25 grains of moisture. If the dew point is below 32° F., the precipitation will appear as frost or snow.

SUMMARY

The calorie is the amount of heat required to raise the temperature of 1 gm. of water 1° C. In heat exchange, calories lost equal calories gained.

The specific heat of a substance is the number of calories required to raise the temperature of 1 gm. of that substance 1° C. Weight

in gm. × change in temperature (Centigrade) × specific heat equals calories. Weight in lb. × change in temperature (Fahrenheit) × specific heat equals B.T.U.'s.

Fusion is the process of changing from the solid to a liquid state. The temperature at which the change occurs is the melting point. Increase in pressure raises the melting point of substances that contract when solidifying, and lowers the melting point of substances that expand during solidification.

To change 1 gm. of ice at 0° C. to water at the same temperature requires 80 calories; the same amount of heat is lost when 1 gm. of water freezes.

The boiling point of a liquid may be defined as the temperature at which the pressure of its vapor equals the atmospheric pressure. An increase in pressure raises the boiling point; a decrease in pressure lowers the boiling point.

Distillation, a process consisting of evaporation and condensation, is used to purify substances or to separate liquids having different boiling points.

To change 1 gm. of water at 100° C. into 1 gm. of steam at the same temperature requires 536 calories; the same amount of heat is set free when the steam condenses.

Evaporation requires heat. This heat is taken from the surrounding medium, thus lowering its temperature. Artificial ice is made by the application of this principle.

The amount of water vapor air *can* hold at a given temperature is its capacity; the amount of water vapor the air *does* hold is its absolute humidity; absolute humidity divided by capacity equals relative humidity.

Cooling the air increases the relative humidity. Warming the air decreases the relative humidity.

QUESTIONS

1. Why do streets dry so rapidly on a windy day?

2. Does fanning cool the face when one is not perspiring? Explain.

3. Food is sometimes kept in thick-walled porous vessels which have been immersed in water before using. Under what atmospheric conditions are such "iceless refrigerators" efficient?

4. Why is it difficult to keep cool in summer when the relative humidity is above 90%?

5. Is water any hotter when boiling vigorously in an open vessel than when boiling slowly? Try to find in the answer to this question a suggestion as to one method of reducing gas bills.

6. Why do clothes sometimes "freeze dry" ?

7. Why does steam produce a more severe burn than boiling water at the same temperature?

8. The steam that enters a radiator may be the same temperature as the water that leaves it. How has the room been warmed?

9. Why do snow and ice melt so slowly in the spring, even when the temperature is considerably above the freezing point?

10. Why is it difficult to hard-boil eggs in an open vessel at the top of Pike's Peak?

11. Explain why sea water freezes less easily than fresh water.

12. What are the advantages of the pressure cooker?

PROBLEMS

1. How many calories will be liberated by 20 gm. of steam upon condensing? How many additional calories will be liberated when the water formed by the steam in condensing cools to 60° C.?

2. How many calories of heat are set free by 10 gm. of steam on condensing, cooling to 0° C., and then freezing?

3. How many grams of ice can be melted by 40 gm. of steam?

4. How many gm. of ice at 0° C. are needed to lower the temperature of 1000 gm. of water from 80° C. to 40° C.?

5. How many calories of heat are needed to heat 100 gm. of water from 50° C. to 100° C. and then vaporize all the water?

6. A copper calorimeter weighs 200 gm. Its specific heat is 0.09, and its temperature is 10° C. How many gm. of steam are needed to raise the temperature of the calorimeter to 80° C.?

7. What weight of aluminum at a temperature of 200° C. will be needed to melt, raise to the boiling point, and vaporize 100 gm. of ice at 0° C.? Use 0.22 as the sp. ht. of aluminum.

8. What will be the final temperature when 20 gm. of ice at 0° C. are mixed with 400 gm. of water at 30° C.? (*Hint.* Let x equal the final temperature. $400(30-x)$ times 1.00 equals calories lost. 20×80, plus $20(x-0)$ times 1.00 equals calories gained.)

9. 100 gm. of ice, 300 gm. of ice water, and 20 gm. of steam are mixed. Find the resulting temperature.

10. 40 gm. of steam, 100 gm. of water at 100° C., 200 gm. of ice, and 400 gm. of ice water are mixed. Find the resulting final temperature.

11. 10 gm. of steam at 150° C. are mixed with 200 gm. of ice water and 60 gm. of ice at −20° C. Find the resulting temperature.

CHAPTER 12

HEAT—METHODS OF DISTRIBUTION

Vocabulary

Conduction, transmission of heat from molecule to molecule.
Convection, transmission of heat by the intermingling of the heated masses.
Radiation, transmission of heat energy by rays or waves.
Insulator, a substance that does not conduct heat.

279. Distribution of Heat. We know that heat comes from the sun and from some other sources. Since heat can be transferred from one body to another, we may inquire how heat is distributed. From the furnace in the basement the heat must be distributed to the rest of the house. It is of interest to inquire how the heat is transferred or transmitted, since it may be possible to hasten or to check such distribution. A radiator, a fireplace, or a stove must furnish heat to an entire room. It has been found that there are three distinct methods of transferring heat energy: *conduction*, *convection*, and *radiation*.

A. CONDUCTION

280. Conduction of Heat. If the bowl of a silver spoon is put into a cup of hot coffee, the handle soon becomes hot enough to burn the fingers. If we hold one end of a stove poker while the other end is inserted in a bed of live coals, in a few minutes the entire poker becomes too warm to be held comfortably. In some manner the heat has been *conducted*, or *led*, from one end of the solid to the other. The molecules of the coals are in rapid vibration. The molecules of the poker which are adjacent to the coals receive some of

this heat energy, which is transmitted by them to other molecules. *Such transmission of heat from molecule to molecule is called conduction.*

281. Conduction in Solids. The *conductometer* of Fig 329 has several rods made of different metals, all mounted on a metal base. The rods are covered with paraffin or a paint that changes color when heated. When steam is passed through the base of the apparatus, the paraffin melts most quickly on the best conductor. The order of conductivity of the five metals used in this experiment is as follows: copper, aluminum, brass, iron, and German silver.

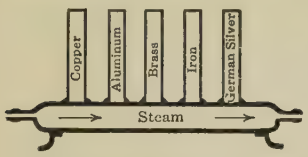


FIG. 329. — Conduction of heat.

Silver is the best conductor of heat known; copper and aluminum are much better conductors than other common metals. German silver, sometimes called nickel silver, is not a good conductor. It does not contain any silver; it is an alloy of nickel, zinc, and copper. The metals conduct heat better than wood does. See Table 11 in Appendix C for the relative conductivity of some common substances. Wool, cotton, and silk are quite porous. They are rather poor conductors of heat. Sawdust is a poorer conductor of heat than wood, on account of the air spaces between the particles.

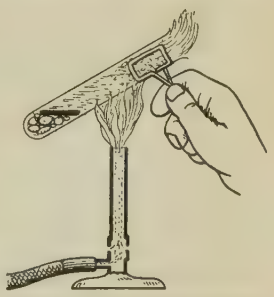


FIG. 330. — Water is a poor conductor.

282. Conductivity of Liquids and Gases. If we put a piece of ice in the bottom of a test tube, weight it, and then fill the tube nearly full of water, the water at the top of the tube may be boiled for some time without melting the ice. (See Fig. 330.) This experiment shows that water is a poor conductor of heat. A still more sensitive test can be made

by the use of the apparatus of Fig. 331. The bulb of an air thermometer is surrounded with water in a large funnel. The stem of the thermometer dips into a bottle containing some colored liquid. Ether is poured on the surface of the water and set on fire. The air thermometer is very sensitive, but the liquid column *C* is lowered only a trifle. The water layer evidently does not conduct the heat from the burning ether to the bulb of the thermometer. From both of these experiments we must conclude that water is a poor conductor; other liquids are also poor conductors.

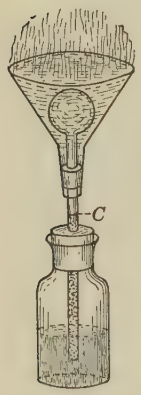


FIG. 331.—Use of air thermometer to show poor conductivity of liquids.

Gases are poorer conductors than liquids. Silver conducts heat more than 800 times as rapidly as water, and almost 20,000 times as fast as air. Non-conducting layers of air in porous solids are largely responsible for their poor conductivity. A vacuum is practically a non-conductor, or a heat *insulator*.

283. Conductivity and Sensation. The tiled floor of a bath room feels colder than a rug in the same room, although a thermometer would show that both have the same temperature. The tiling is a better conductor of heat; hence it *takes heat from* the foot faster than the rug does. In removing a pan of bread from the oven, we get a more severe burn if we touch the pan than by touching the bread. Both have the same temperature, but since the metal is the better conductor, it *transmits heat to* the hand more rapidly. In winter, cotton or linen sheets feel much colder than woolen blankets, because they are better conductors.

Clothing does not afford us any warmth in winter, but it prevents the heat of the body from escaping. That kind of clothing which is made of the poorest conducting material seems warmest. Furs are very warm because they contain layers of non-conducting air. Two light garments are warmer

than a single heavy one because there is a layer of non-conducting air between them. Silk and wool are poorer conductors than cotton and linen.

284. Applications of Conductivity. Aluminum is much used for cooking utensils. There are several reasons, but one of them is the fact that it is a good conductor of heat. Copper is used by some automobile manufacturers for the radiator tubes. The outer surfaces of the cylinders of rotary airplane engines, motor cycles, and air-cooled automobiles are deeply corrugated. The heat is conducted to the outer surface by these metals, and carried away by a stream of air.

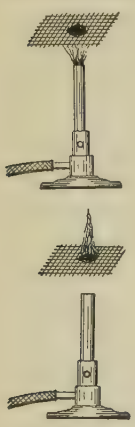


Fig. 332. — Metal gauze conducts heat so rapidly that gas is not enkindled.

When a wire gauze is held over a burner, the gas may be lighted either above or below the gauze. (See Fig. 332.) The gauze conducts the heat away so rapidly that the gas on the opposite side from the flame is not heated to its kindling temperature. The miner's safety lamp, invented by Sir Humphry Davy, depends upon this principle. (See Fig. 333.) The flame of the lamp is surrounded by wire gauze, which prevents the ignition of explosive gases that may be present in the surrounding atmosphere.

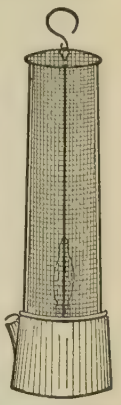


Fig. 333. —Davy safety lamp.

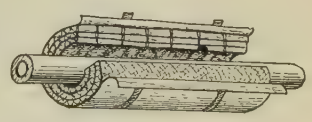


Fig. 334. — Heat insulator.

285. Non-conductors or Heat Insulators. In a large number of cases, insulating material is used to prevent the loss of heat. Steampipes in the basement and in the walls of houses are covered with insulating material. (See Fig. 334.) Furnaces are covered with "85% magnesia," a substance that

is very porous, or with corrugated asbestos to keep the heat from escaping to the basement. Houses are built with double walls and in cold climates with double windows. The dead air spaces in the walls keep the heat from escaping in winter and the outside heat from coming in during hot weather. Thus the house is warmer in winter and cooler in summer if well insulated. A blanketing material is now frequently used to cover the sheeting for houses. Brick veneer houses are very warm in winter and cool in summer, if the brick course is kept about an inch from the sheeting to leave an air space. (See Fig. 335.) Hot water storage tanks have their hollow walls filled with mineral wool, a good insulator.

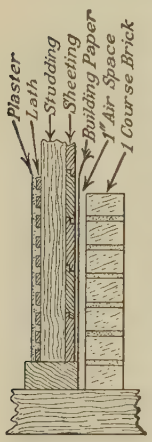


FIG. 335.— Brick veneer construction.

286. The Fireless Cooker. The so-called "fireless cooker" is used to conserve heat. There are two types that are in use.

1. In the simplest type of fireless cooker a pail or tub is lined with several inches of insulating material, leaving

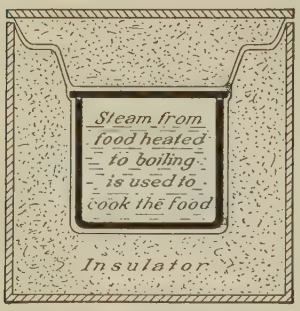


FIG. 336. — Fireless cooker.

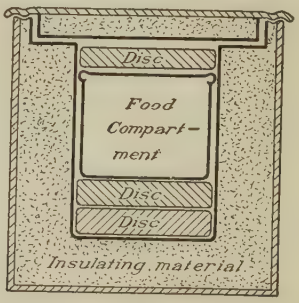


FIG. 337.— Hot discs cook the food in the insulated container.

space at the center for the cooking utensil. The food is first heated to boiling and then put inside the fireless cooker.

Since the loss of heat by conduction is small, the food is slowly cooked by the heat which is thus conserved. (See Fig. 336.)

2. In another type of fireless cooker, soapstone discs having a high thermal capacity are heated to a high temperature and put into aluminum containers that are thoroughly insulated. Food in smaller containers is then placed upon the hot discs. The heat from these discs of stone is sufficient to cook the food. (See Fig. 337.)

287. Fireless Ranges. To conserve gas, so-called fireless gas ranges are now used for cooking. The oven is double-walled, and the space between the walls is filled with mineral wool or some other insulator. (See Fig. 338.) When a roast

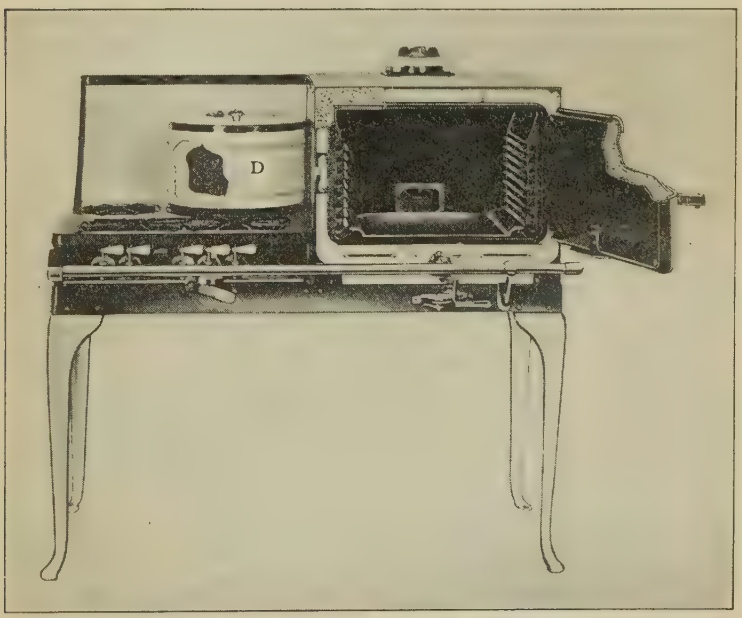


FIG. 338. — The oven walls are insulated. The thermodome at the left has its walls filled with insulating material.

is put in such an oven, the gas is lighted and kept burning for about half an hour. Then it is turned off, and the oven is sealed. The heat stored in the walls of the oven is sufficient to finish the cooking of the roast.

For cooking foods by boiling, a thermodome is used. (See D of Fig. 338.) This is a thick-walled device which surrounds all the upper part of the cooking utensil while the water inside is being heated to boiling. It has a high heat capacity and absorbs heat which would otherwise escape around the sides of the vessel. After about 10 minutes, the gas is turned off, and the thermodome is lowered until it completely encloses the cooking utensil. The heat which it had absorbed is now supplied to the food; it is sufficient to complete the cooking.

288. The Thermos Bottle. Thermos bottles are generally made of glass blown with double walls, as shown in Fig. 339. The air is then exhausted from the space between the walls. Since a vacuum is a non-conductor, a hot substance put in the bottle retains its heat; a cold substance put in the bottle remains cold, since it cannot receive heat from the outside. The glass is silvered to prevent the transmission of radiant heat. Some large thermos bottles are mounted on motor trucks and used to keep milk cold while it is being transported.

FIG. 339. — Thermos bottle. (Sectional.)

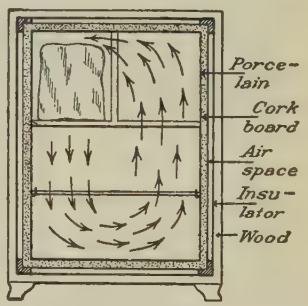


FIG. 340. — Refrigerator walls are insulated.

289. The Refrigerator. The old saying, "What will keep out cold will keep out heat," has much in it that is true. Our refrigerators are built with this idea in mind. A good re-

frigerator should have double or triple walls. The space between the walls should be filled with cork board, or some other heat insulator. The door should close tightly, and it should always be kept closed as much as possible. Fig. 340 shows the construction used in a good refrigerator, and also the manner in which the air inside the refrigerator circulates.

B. CONVECTION

290. The Principle of Convection. We have learned that substances expand when heated and that their density is correspondingly decreased. That means, for example, that air over a heated area is less dense than the surrounding air. The colder, heavier air will displace this lighter air and push it upward. Thus currents are produced. Suppose we add a few particles of sawdust to a beaker of water and heat the beaker near one side. (See Fig. 341.) The water directly over the flame is more highly heated; it expands, and is pushed upward by the heavier and colder water from *A*. The circulatory movement of the water can be observed by the movement of the sawdust particles.

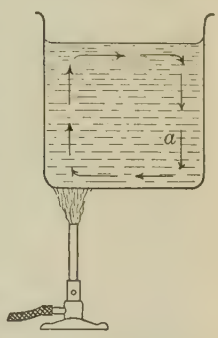


FIG. 341. — Convection currents.

Convection currents may be produced in either liquids or gases. By means of such currents *heat is transmitted by the movement of the heated masses.*

291. Ventilation. The whole plan of ordinary ventilation depends upon convection. The air which we exhale is warmer and lighter than the air out-of-doors. If we open one window of a room at the top, the foul air may be pushed out by fresh air as it comes in through an opening nearer the floor. The three diagrams of Fig. 342 show clearly how convection currents are useful in ventilating rooms. In

the ventilation of mines and large buildings, compressed air is often used.

292. Draft of a Chimney. Before a fire is started in a furnace or a stove, the air in the chimney may have the same density as the air outside the chimney. Then there is no draft. When a fire is first started, the air above the fire is heated, and it expands. The cold, heavy air from outside enters the furnace and pushes up the chimney the hot gases formed by combustion.

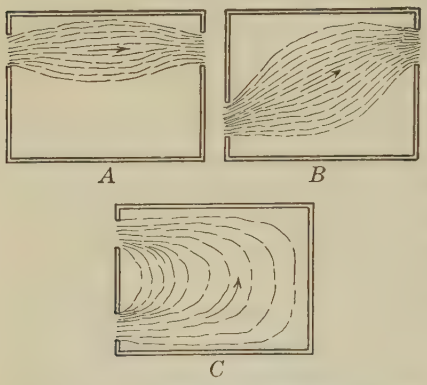


FIG. 342. — Arrangement of openings for ventilation.

A tall chimney produces a better draft than a short one, since there is a greater difference in weight between the hot gases inside the chimney and an equal volume of cold air outside. (See Fig. 343.) The student should not forget that a draft may also be produced by the wind blowing across the top of a chimney. (See § 70.)

293. Atmospheric Circulation. 1. *Land and sea breezes.* Since the land has a lower specific heat than water and it is not so mobile, it heats more rapidly in the daytime. The air over this heated area is pushed upward by the cooler air from the sea; therefore about the middle of the forenoon a cool sea breeze begins to blow toward the land, Fig. 344. At night the land cools more quickly, the warmer air over the water is forced upward, and a land breeze is produced. Fishermen along the coast go to sea at night with the land breeze, and return in the forenoon with the sea breeze.

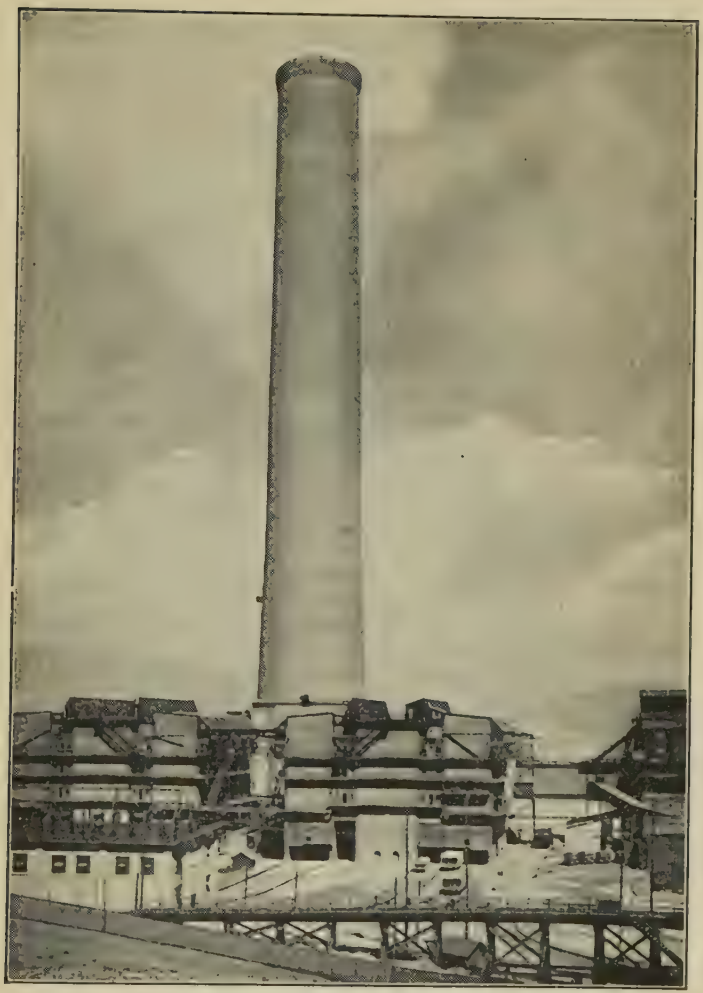


FIG. 343. — This stack, built for smelting copper ores in Montana, is so large that the Washington Monument would disappear from view if it were placed inside. Its height is 583 feet.

2. *Monsoons* are huge *seasonal* land and sea breezes. In summer, the land area is intensely heated and the wind blows toward the land continually. In winter, the conditions are reversed, and the wind blows toward the sea.

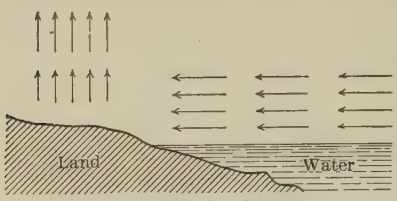


Fig. 344. — Sea breezes.

3. *Trade winds.* The *trade winds* are also produced by convection currents. The direct rays of the sun in the vicinity of the equator produce upward air currents. The trade winds then blow toward the equator throughout the year. They do not blow due north and south, since they are deflected toward the west by the rotation of the earth on its axis. The chart, Fig. 345, shows the general direction of the winds as they blow over the earth's surface. The student should note from the arrows that the air over the equator is being pushed upward by the colder air drifting toward the equator. Where the air is rising, we have the *equatorial calm belt.* The air currents at the Tropics are downward. At the Tropics we have the *Calms of Cancer and Capricorn.* This chart shows conditions as they exist in the spring and fall. During our summer season, these calm belts shift northward; they shift southward during our winter season.

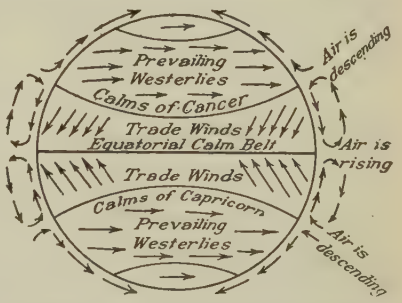


Fig. 345. — Chart to show atmospheric circulation.

294. Heating Systems. 1. *Hot-air.* In *hot-air* heating systems, the heat is distributed by convection currents. The

cold air usually enters from out-of-doors directly, Fig. 346, circulates around the fire-box, and then rises to the rooms.

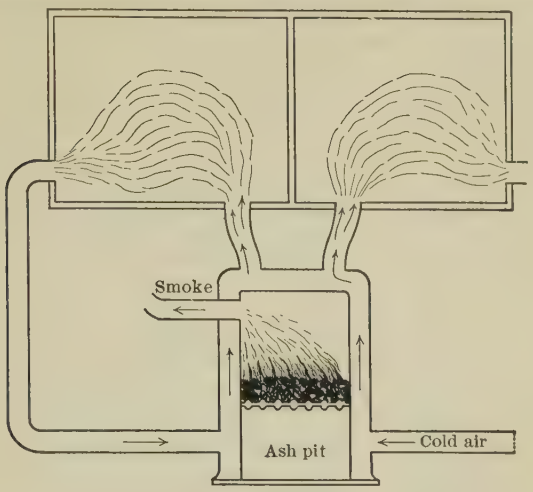


FIG. 346. — Hot-air heating system.

A part of the air then escapes through doors and windows, while in some systems a part returns to the furnace, where it is mixed with fresh air and reheated.

Some hot-air furnaces now in use are *pipeless*. Such furnaces depend entirely on convection currents to distribute the heat to all parts of the house. The furnace of Fig. 347 has one large register directly over the furnace. The hot air rises from the center of the register, circulates through the rooms by way of transoms and doors, and returns to the furnace to be reheated. The

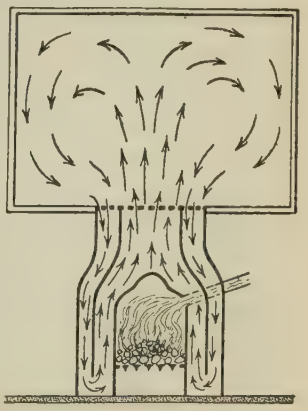


FIG. 347.— Pipeless furnace.

register is composite, having an opening in the center for the heated air, and an annular opening surrounding the former through which the air is returned for reheating.

2. *Hot-water.* In some houses *hot-water* heating systems are installed. The principle is the same as that used in hot-air systems, but in this case water is warmed and convection currents are set up in the water. The water which circulates around the fire-box is heated and rises to the radiators. Here it loses heat to the room by radiation, and then returns to the bottom of the furnace to be reheated.

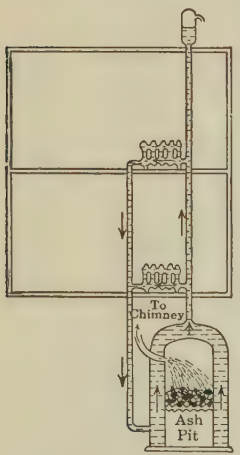


FIG. 348. — Hot-water heating system.

In such a system the radiators must be larger than those used with steam-heating systems, since the water is not heated to boiling. Generally it is not heated to more than 160° F. in cold weather, and much less in mild winter weather. Two pipes must be used, one for the entrance of the hot water, and the other as a return pipe. An expansion tank is always connected with the system to accommodate the increased volume which the water occupies when heated, and also to act as a safeguard for the escape of steam if the water should boil. The arrows of Fig. 348 show the direction of the circulation of the water by means of convection currents. To make such circulation less sluggish, a mercury column is sometimes used to accelerate it. In the room, convection currents are set up in the air, since the air above the radiator is warmed. Thus the heat is transferred to the room.

3. *Steam-heat.* In *steam-heating* systems the water is heated to boiling, and the steam, which occupies several hundred times as much volume as the water had occupied,

expands through the pipes and into the radiators. As the steam condenses in the radiators, each gram sets free 536 calories of heat; or each pound liberates 965 Btu. This heat is utilized in warming the room. The heat from the radiator is distributed to the room by convection and by radiation. After condensation occurs, the water returns to the boiler, usually through the same pipe. In large buildings, where the volume of water formed by condensation is greater, a separate pipe is used as the return pipe. Fig. 349 shows the arrangement of furnace and radiators in a steam-heating system.

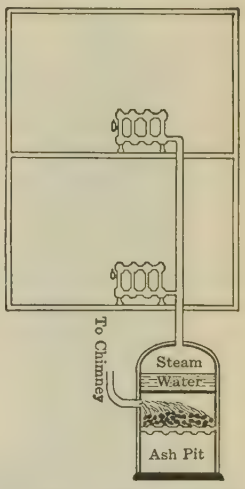


FIG. 349.— Steam-heating system.

4. *Vapor-heat.* The *vapor-heating* system uses the same type of boiler that is used in the steam-heating system. We know that water boils at a lower temperature under reduced pressure. In the *vapor* system some method is used to get rid of part of the air in the pipes and radiators. This may be done by means of a pump or by use of the ejector principle. Of course two pipes must be used in such a system, and the radiators and connecting pipes must be kept gas-tight. If the pressure inside such a system is reduced to one half an atmosphere, the water will boil at about 180° F.

295. Heating Systems Compared. 1. The hot-air system is less expensive to install. It is easily controlled in mild weather, when little heat is needed. There are no unsightly radiators. However, dust and dirt get into the house more readily from the cold air inlet. It is sometimes difficult to heat the rooms on the windward side of the house. In severe weather the system is considered less efficient than other systems.

2. Steam-heating systems are less expensive to install than hot-water and vapor systems. They are efficient in cold weather, especially in large buildings where pressure boilers are used. On the other hand, such a system is hard to control in the spring and fall when only a little heat is needed. The house cools off quickly when the fire is banked at night. The radiators take up room and are generally inartistic.

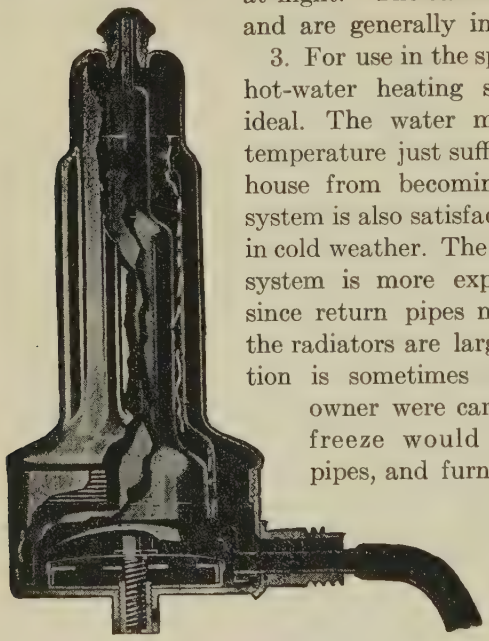


Fig. 350. — Vacuum valve.

3. For use in the spring and fall the hot-water heating system is almost ideal. The water may be kept at a temperature just sufficient to keep the house from becoming chilly. Such a system is also satisfactory and efficient in cold weather. The hot-water heating system is more expensive to install, since return pipes must be used and the radiators are larger. The circulation is sometimes sluggish. If the owner were careless, of course a freeze would crack radiators, pipes, and furnace.

4. The vapor-heating system combines the advantages of the steam and hot-water heating systems. It is efficient, and easily controlled in all kinds of weather. The radiators are larger than those used for steam, but smaller than those used with hot water. Unfortunately, this system is more expensive to install than any of the other systems.

296. Radiator Valves. We have learned that steam cannot come into the radiators unless there is some way for the

air to get out. The ordinary valve, Fig. 294, contains a collapsible compartment filled with a liquid which has a low boiling point. The air can be pushed out by the steam as it enters, but the heat causes the liquid to evaporate. By the expansion of its vapor the valve closes the opening so that no steam can escape.

Sometimes vacuum valves are used to prevent the air from re-entering the radiator when the fire is checked and the steam all condenses. Thus a partial vacuum is produced, and the water will boil at a lower temperature under the reduced pressure. It is easier to get up steam in such cases. In mild weather, or after the fire is banked at night, hot vapors much below 100° C. are given off to the radiators. Fig. 350 shows one type of vacuum valve.

297. Hot-water Tank. The method of heating water for the kitchen, bath, or laundry differs little from the hot-water heating system of heating houses. A heating coil is placed in the furnace, or just outside so that steam flows around it. Quite often gas is used to heat the water in the coil. As this water is heated and expands, it is pushed up to the top of the storage tank by the colder, heavier water which enters near the bottom of the tank. (See Fig. 351.) When hot water is drawn off from the top of the tank, more cold water enters from the pipe near the bottom. Convection currents are set up in the direction shown by the arrows.

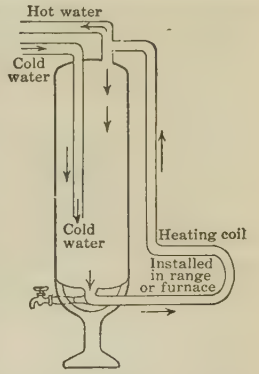


FIG. 351.—Hot-water tank.

C. RADIATION

298. Radiation. When the hand is held in front of a fireplace, Fig. 352, it is warmed by radiation. In the same manner we receive heat from the sun. Since heat is a form

of energy produced by the motion of the molecules, waves are set up in the surrounding medium. Huygens advanced the wave theory to account for the transmission of radiant energy. Radiations travel through a vacuum; so he presupposes the existence of a very subtle medium which pervades all space and transmits radiant energy. This medium is called *ether*. It is supposed to be an invisible fluid, so very rare that it cannot be weighed or measured; it easily penetrates intermolecular spaces. *The absorption of radiant energy produces heat in the absorbing medium. Substances easily penetrated by the ether waves are little warmed by their passage.*

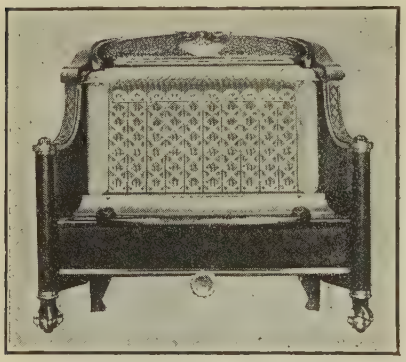


Fig. 352. — Heating by radiation.

299. Absorption, Reflection, and Radiation of Heat. When heat waves are incident upon an object, a part are reflected, a part may be transmitted, and the rest are absorbed. Polished metals are the best reflectors known; hence they are very poor absorbers of heat. A poor absorber of heat is also a poor radiator. A roughened tea-kettle absorbs heat more readily than a highly polished one; it also loses heat faster by radiation.

The color of a substance also affects its absorbing power. A black surface absorbs heat faster than a white one. Hence light-colored garments are cooler in summer sunshine than black ones. Lampblack is the best absorber known and also the best radiator.

Crookes' radiometer may be used to demonstrate these facts. It consists of a partially exhausted bulb, in which

is suspended a light aluminum wheel that has a set of vanes in its circumference. Each vane is polished on one side and covered with lampblack on the other. When exposed to a source of radiant energy, heat is absorbed more rapidly by the black surfaces. The adjacent air is more highly heated and rebounds with a greater velocity from the black surfaces, thus exerting greater pressure and causing the wheel to rotate in the direction shown in Fig. 353.

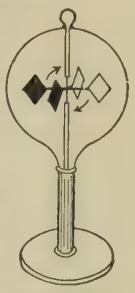


FIG. 353.—Crookes' radiometer.

By the use of Leslie's cube and a differential thermometer, Fig. 354, it may also be shown that a black surface radiates heat faster than a white one. Surfaces of the cube are painted different colors. It is filled with hot water and supported so that the black face will be the same distance from bulb *A* of the thermometer that the white face is from bulb *B*. Since bulb *A* is heated more rapidly by radiation from the black surface, the air within this bulb expands more and forces the liquid *C* down the tube.

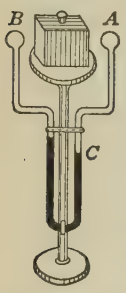


FIG. 354.—Leslie's cube and differential thermometer.

300. Laws of Radiation. When the moon comes between the sun and the earth during an eclipse of the sun, it cuts off both the heat rays and the light rays at the same time. Since light is known to travel at a velocity of 186,000 miles per second, we conclude that heat waves travel at the same velocity. Heat waves also travel in straight lines.

A person sitting near a fireplace receives more heat than one who is farther away. The higher the temperature of a radiator, the more heat waves it gives off by radiation. Measurements show that the *intensity of radiant energy is directly proportional to the temperature of the source, and inversely proportional to the square of the distance.* The planet Mercury is only about

one third as far from the sun as the earth; hence it must receive about nine times as much radiant heat as the earth receives.

Suppose we put two cups of hot water in a refrigerator to cool. The refrigerator has a temperature of 50° F.; one cup of water has a temperature of 60° F., and the temperature of the other is 70° F. By the use of a thermometer it may be shown that the latter cools twice as fast as the former. It is 20° warmer than the refrigerator and the former is only 10° warmer. NEWTON'S LAW OF COOLING may be stated as follows: *The rate of cooling by radiation is proportional to the difference between the temperature of the cooling body and the surrounding medium.* A house at 60° F. cools off much faster when the outside air is 20° F. than it does when the temperature is 40° F.

301. Heat Transparency. When the ether waves produced by radiant energy pass through a substance without heating it, the substance is said to be *diathermanous.* Substances opaque to heat are *athermanous.* Dry air is quite transparent to heat, but air containing much water vapor is much more opaque. Clouds absorb heat as it travels from the sun to the earth, and they prevent, to a great extent, the loss of heat from the earth by radiation. On high mountains the sun's heat is intense.

Some substances are transparent to light, but opaque to heat. Alum is an example. Conversely, iodine solution is opaque to light, but transparent to heat.

Heat from the sun readily comes in through glass windows, but heat from the radiators does not pass out through glass readily. If the temperature of the source of heat is very high, its waves are short and very penetrating. The heat waves given off from a radiator are long waves and much less penetrating. Glass is used for covering greenhouses and "cold frames"; the heat from the sun passes in through the glass, but there is little loss by radiation.

SUMMARY

Heat may be transmitted by conduction, convection, and radiation. Solids conduct heat better than liquids or gases. Convection does not occur in solids.

Good conductors feel hotter than they really are, if their temperature is higher than that of the hand; when their temperature is lower than the hand, they feel colder.

Heat insulation is extensively used in house construction, building refrigerators, covering pipes, and in fireless cookers.

Convection depends upon the fact that fluids expand when heated. Ventilation systems, hot-air and hot-water heating systems, and atmospheric circulation all depend upon convection currents.

Good absorbers of heat are good radiators. Good reflectors are poor absorbers and poor radiators.

QUESTIONS

1. Why does wrapping ice in a woolen blanket keep it from melting rapidly? Is ice of much value in a refrigerator unless it melts? Explain.

2. Why does a chimney "draw"? How does the height of the chimney affect the draft? Why does a chimney "draw" better on a clear, cold day than in damp, cloudy weather? Explain why a chimney "smokes" when a new fire is started.

3. Why are houses built with hollow walls?

4. Why do stove lifters and pokers usually have wooden or coiled wire handles?

5. Why do workmen around furnaces wear woolen clothing even in summer?

6. Does clothing supply us any heat in winter? How does it keep the body warm?

7. How does snow protect the grass in winter?

8. In making ice-cream, why is the cream usually put in a metal container and the ice in a wooden vessel?

9. Is it economy to keep stoves highly polished? Explain.

10. Why does dew or frost seldom form on cloudy nights?

11. On high mountains the sun is exceedingly hot in the daytime, but the temperature usually falls below freezing at night. Explain.

12. Why does it rain nearly every afternoon in the equatorial regions?

13. Why is it necessary for a radiator to have more sections when used with hot water than with steam heat?

14. Does tea cool more quickly in a tarnished metal pot or in a highly polished one?

15. Which is warmer, cotton clothing or linen? Why?

16. Why does mist often form in the receiver of an air pump?

17. Water kept in earthenware jars is much cooler than the surrounding air. Explain.

18. Why is silvered glass used in making the thermos bottles?

19. Two pieces of cloth are laid upon the snow. One of them is black; the other, white. The black one sinks into the snow faster on a sunshiny day. Why? If we cover the black one with powdered alum and the white one with powdered iodine, the condition will be reversed. Explain.

20. In what way do double windows save fuel?

21. Why are steampipes in the basement covered with asbestos or magnesia?

22. Why does the tongue or a moistened finger freeze to a cold metal, but not to wood of the same temperature?

23. Is it economical to have steam radiators highly polished? Would it be economical to have them painted black?

24. How does heat get from the radiators to the various parts of a room?

25. Make a list of at least six heat insulators used in a dwelling house.

CHAPTER 13

HEAT AND WORK

Vocabulary

Mechanical equivalent, the value of heat units in terms of work units, or vice versa.
Reciprocating, to and fro.
Turbine, a rotary motor driven by water or steam.

302. Heat and Work. We rub our hands to warm them. The friction, which is *wasted work*, is transformed into heat. A gimlet used to bore a hole in a block of wood is heated by friction. Impact also produces heat, since it produces internal friction between the molecules. A bullet fired against a target may be melted by the heat of impact.

James Prescott Joule, the English physicist who stated the law of the conservation of energy, devised an apparatus for finding out how much work must be done to produce one British thermal unit of heat. He permitted known weights to fall through a measured distance. (See Fig. 355.) Of course the weight times the distance equaled the work done. In falling, these weights turned a set of paddles which were immersed in a known weight of water. No *useful* work was accomplished, since the paddles merely heated the water by friction. The rise in temperature of the water enabled him to calculate the amount of work needed to produce one British thermal unit of

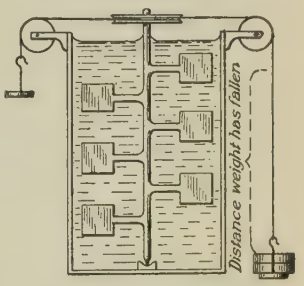


FIG. 355. — All the work is changed into heat energy.

heat. He found that 772 ft. lb. of work are equivalent to one B.T.U.

Recent measurements show that 778 ft. lb. is a more accurate figure. In the Metric system *this is equivalent to 427 gram meters of work per calorie.* In terms of work the calorie may be defined as 4.19×10^7 ergs, or 4.19 joules.

303. How Heat Is Converted into Work. Since wasted work is converted into heat, conversely *heat energy can be changed into mechanical energy,* which is capable of doing work. One British thermal unit of heat can do 778 ft. lb. of work; one calorie of heat can do 427 gm. m. of work. These numbers are called the *mechanical equivalents of heat.*

Biologists tell us that a thick slice of bread, when oxidized, furnishes 100 *large* Calories, or 100,000 *small calories* of heat. If a thick slice of bread is oxidized in the body, and all its heat is converted into muscular energy, it should do 42,700,000 gm. m. of work. Under such conditions, the heat energy would enable a man weighing 150 lb. to climb to the top of a mountain 2000 ft. high. Of course a part of the heat energy from our food is used to maintain the body temperature at 98.6° F., summer or winter. Some of our food is utilized for nutrition and repair. Experiments carried out by Professor Atwater of Wesleyan University showed that only 28% of the heat energy of the food was converted into muscular energy.

When water is converted into steam, it expands about 1600 times and exerts pressure in all directions. In a boiler the steam is confined until it reaches a high pressure. By pipes it is conducted to the cylinder of a steam engine, where it expands and pushes a piston back and forth in the cylinder. Heat from burning coal or oil produces the steam, and this heat energy is transformed into mechanical energy as it moves the piston. One pound of good coal may produce 15,000 B.T.U. If all this heat could be converted into work, one pound of such a coal would be equivalent to

15,000 × 778 ft. lb., or 11,670,000 ft. lb. of work. For every pound of coal burned per hour, we should get $\frac{11{,}670{,}000}{550 \times 60 \times 60}$, or about 6 H.P. continuously. In practice, the ordinary steam engine uses about 1.5 lb. of coal to produce 1 H.P. per hour, an efficiency of only 11%. Some of the most efficient steam engines use 0.8 lb. of coal per H.P. hour, an efficiency of about 20%.

Such low efficiency is not surprising if we consider that nearly 30% of the heat energy goes up the chimney during combustion. About 50% of what remains is lost from the fact that not all the expansive force of the steam can be utilized. The diagram of Fig. 356 shows how the heat energy is sometimes distributed in a simple power plant.

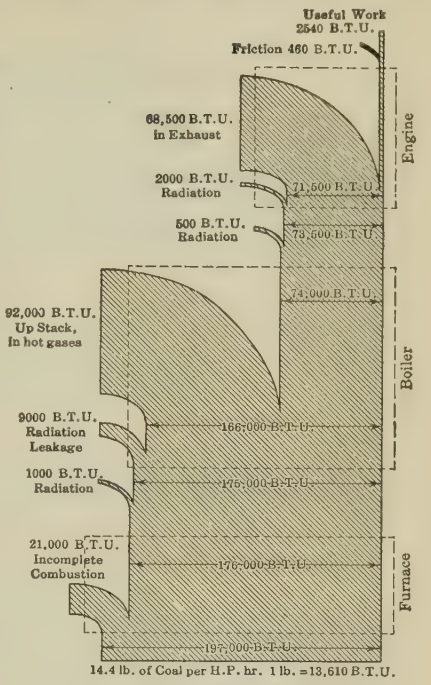


FIG. 356. — Energy diagram.
(*Courtesy of J. A. Randall.*)

In all types of steam engines, the fuel is burned under the boilers to produce steam. They are *external combustion* engines. The so-called gas engines are *internal combustion engines*. Gasoline or other fuel is vaporized and mixed with air in a carburetor. Then this mixture is exploded in a thick-walled cylinder, usually by means of an electric spark. The heat energy produced by such an explo-

sion causes the gaseous products formed by the explosion to expand and push against the piston with great force. Thus heat energy is converted into mechanical energy.

304. Simple Steam Engines. We have already learned that the steam from boiling water expands with great force. The walls of the boiler must be made very strong to resist this

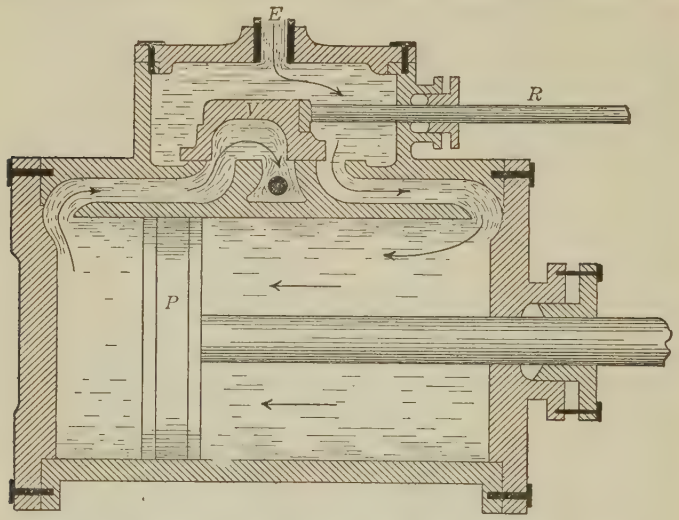


Fig. 357. — Steam engine cylinder and steam chest with valve.

force of expansion. From the boiler, the steam under pressure is led to the steam chest. In Fig. 357 the steam enters the steam chest through the pipe E. When the slide valve V is in the position shown in the figure, the steam will pass on through the steam chest into the right end of the cylinder. Here it expands and pushes the piston P toward the left with great force. The spent steam from the previous stroke passes from the left end of the cylinder and out through the exhaust pipe, represented by the black circle. The path of the steam is shown by the arrows.

The valve V then slides to the right until the left end of

the cylinder is connected with the steam chest, and the right end with the exhaust. Steam enters the left end of the cylinder and pushes the piston to the right. By the movement of the valve, steam is admitted alternately to the ends of the cylinder. Thus the piston is pushed to and fro alternately. Such a motion is called a *reciprocating* motion. The student should observe that the openings in the cylinder are connected alternately with the steam chest and the exhaust by means of the valve.

305. How the Piston Moves the Drive-Wheel or Belt-Wheel. In Fig. 357 we learned how the steam drives the piston forward and backward with a reciprocating motion. If this mechanical energy is to be used to drive the wheels of a

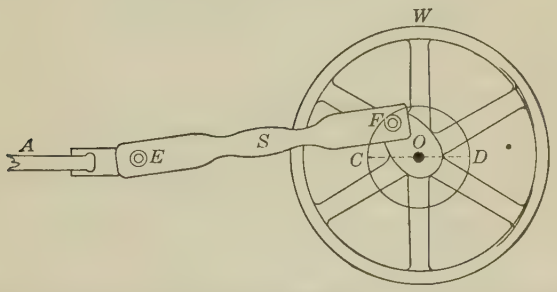


Fig. 358. — Reciprocating motion changed to rotary one by eccentric.

locomotive or to turn a belt wheel, it will be necessary to change such to-and-fro motion into a rotary motion. In the discussion of the sewing machine, § 211, we learned that such a change is not difficult. The end of the piston rod is fastened to one end of the shaft *S* of Fig. 358. The crank pin *F* at the end of the crank *OF* fits into a collar at the other end of the shaft *S*. As the piston moves to the right the length of the cylinder, point *E* moves in the same direction a distance equal to the diameter *CD*. The crank pin moves from *C* to *D* along the half-circumference. During the return stroke of the piston, the crank pin at *F* com-

pletes the revolution along the circumference, while E moves a distance equal to DC. The inertia of the heavy flywheel W carries the piston past the two points where there is no steam pressure, or past dead-center.

306. How the Valves Are Controlled. Of course the slide valve of Fig. 357 must open and close the pipes leading from the steam chest to the cylinder and from the cylinder to the exhaust at just the right time. The rod R which operates the valve is connected by means of the shaft A of Fig. 359 to an eccentric operated by the crank shaft upon which the flywheel turns. The shaft A ends in a collar, which fits around the disc D. This disc rotates about C, an axis which is off center (eccentric). During one half a revolution, the point X moves along the curve as indicated by the arrows, but the end of the shaft at A moves to the left by a distance equal to twice that of CX. As the revolution is completed, the end of the shaft moves to the right an equal distance. While X describes a complete circle, point A moves to-and-fro, at the same time controlling the movement of the valve.

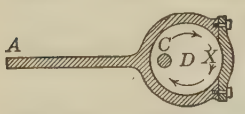


Fig. 359. — Valve controlled by cam or eccentric.

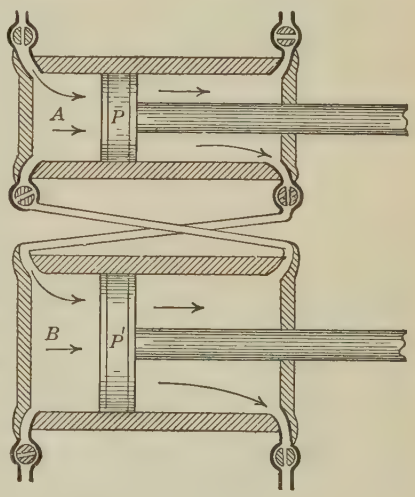


Fig. 360. — Double-expansion engine.

Corliss valves are used in many large steam engines. These valves open and close by turning slightly in the valve seats, Fig. 360. Each of the four valves may be timed independently of the others;

greater efficiency can be obtained by using Corliss valves than by the use of the slide valve.

307. Condensing and Non-condensing Engines. If the spent steam as it escapes from the exhaust goes into the air directly, it must encounter a backward pressure. The air pressure is resisting its motion with a force of nearly 15 lb. per sq. in. Hence if the steam as it comes from the steam chest exerts a pressure of 80 lb. per sq. in., its *effective* pressure will be reduced to only 65 lb. per sq. in. by the backward pressure of the atmosphere. To furnish an *effective* pressure of 80 lb. on each square inch of the piston, the steam must be supplied at 95 lb. per sq. in. Because a higher pressure must be maintained in the boiler, such an engine is called a *high-pressure engine.* It is also called a *non-condensing* engine.

Most stationary engines are fitted with a condenser, in which the exhaust steam is condensed by means of a spray of cold water. Thus a partial vacuum is produced in the condenser, and the backward pressure opposing the motion of the piston is reduced. Sometimes such condensation reduces the back pressure to not more than 1 lb. per sq. in. Thus a boiler pressure of 81 lb. will be approximately as effective with such a *condensing* engine as a pressure of 95 lb. when used with the non-condensing type. Condensing engines are sometimes called low-pressure engines.

308. Compound Engines. Locomotive engines are usually high pressure, non-condensing engines. Locomotives are generally equipped with *compound* engines. (See Fig. 360.) As the steam leaves the first cylinder, it still has expansive force. Hence it is led into a larger cylinder where it expands still further, but in so doing it does useful work against the piston P'. Such an engine is known as a *double-expansion* engine. Triple-expansion and even quadruple-expansion engines are sometimes used.

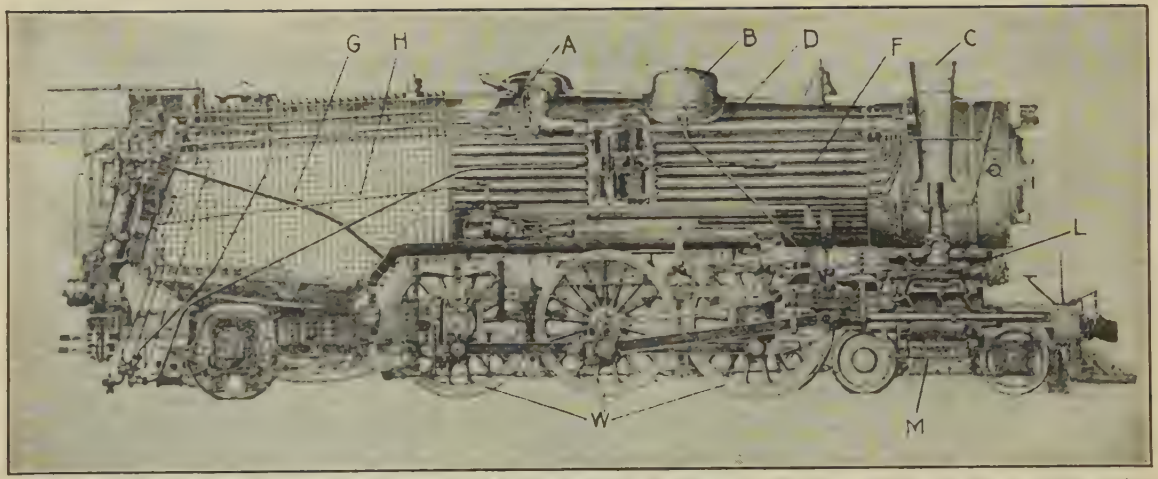


Fig. 361. — Locomotive diagram. A. Throttle. B. Sandbox. C. Smokestack. D. Steam pipe. F. Flue, or boiler tube. G. Sectional brick arch, to protect flues. H. Reverse gear rod. L. Piston valve. M. Piston in cylinder. W. Drive wheels.

From the diagram, it is evident that most of the weight of the locomotive rests on the drive wheels. This enables the wheels to grip the track more firmly, but still the drive wheels of a locomotive sometimes spin around rapidly when the latter is attempting to start a heavy train. Can you explain this? What is the purpose of the sandbox on a locomotive?

A large labeled diagram of the locomotive may be obtained from *Railway and Locomotive Engineering*, 114 Liberty Street, New York.

309. The Boiler. If an ordinary wash boiler is heated over a gas range, steam is produced, but the efficiency is very low because so little surface is exposed to the flame compared with the amount of water that is heated. The boilers used to furnish steam for engines are designed to have the fire and flames come in contact with as large a surface as possible. Two types of boilers are used, the *fire-tube* and the *water-tube*. In the latter type, which is often used with stationary engines, the flames play against the water reservoir and also around a large number of water-filled tubes which are connected with the reservoir. In the fire-tube type, which is used on locomotives, the flames are sucked from the fire-box through long horizontal tubes that are surrounded with water. The exhaust steam escapes through the smokestack and produces a powerful draft. The locomotive diagram of Fig. 361 shows the arrangement of the fire-box and the flues.

With stationary engines the exhaust steam is often used to preheat the water entering the boiler. Such an arrangement is called a *feed water heater*. It is also possible to utilize the heat from the fuel gases for the same purpose, such a device being known as an *economizer*. Both methods increase the efficiency.

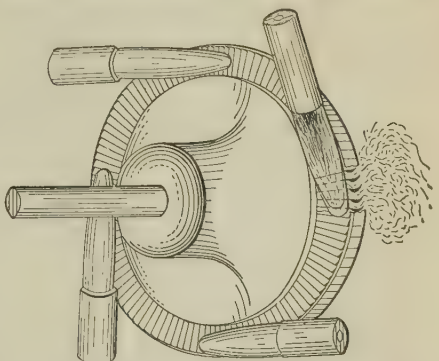


Fig. 362. — Principle of turbine.

310. The Steam Turbine. The steam turbine works on the same principle as the water turbine, or the common windmill. In the Curtis turbine the steam is directed through nozzles against curved blades, as shown in Fig. 362. The principle is the same as that of the Pelton water wheel. From the

first set of movable blades the steam passes to a set of fixed blades, Fig. 363. It is then directed at an angle of high efficiency against another set of movable blades. In this manner it continues until its expansive force is practically spent.

The Parsons and Westinghouse turbines consist of a cylindrical drum or rotor having a large number of blades set much like those of a windmill, Fig. 364 or 366A, and a casing upon the inner side of which there is a large number of fixed blades, Fig. 365. The steam enters near one end of the turbine and flows along the space between the rotor and the casing. As the pressure is thus reduced, the steam expands. The diameters of both the rotor and casing are made larger near the outlet end. The blades are also gradually increased in length. Fig. 366 shows the Westinghouse rotor with nozzle and reversing chamber.

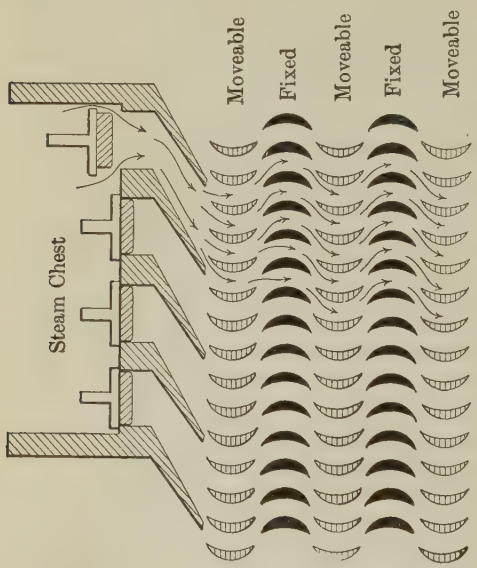


FIG. 363. — Path of steam through Curtis turbine.

311. Advantages and Disadvantages of Turbines. Turbines are extensively used on large ocean liners and destroyers, especially when high speed is desirable. For a given horse power, they occupy much less space than the reciprocating engine. The to-and-fro motion of the piston of a reciprocating engine causes a great deal of vibration, while a steam

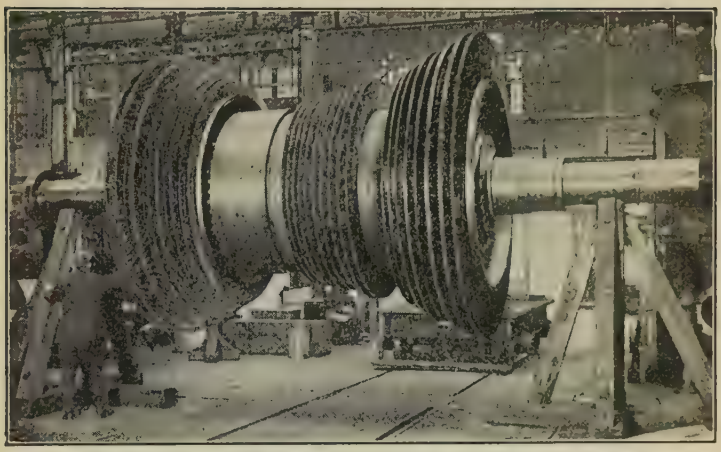


FIG. 364. — Rotor of Westinghouse turbine. 12 feet in diameter.

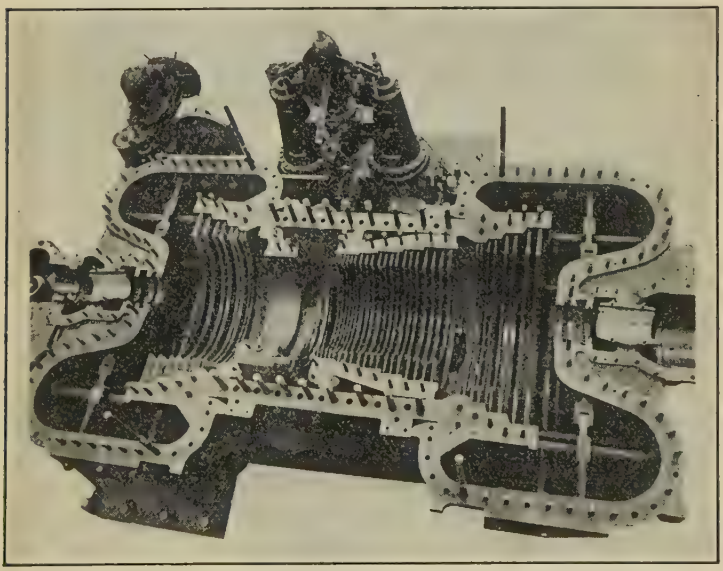


FIG. 365. — Stator base for a 25,000 kilowatt Westinghouse turbine.

turbine runs more steadily. The turbine is also more efficient when working at a maximum capacity. It does not work well at a low speed. The chief disadvantage of the turbine

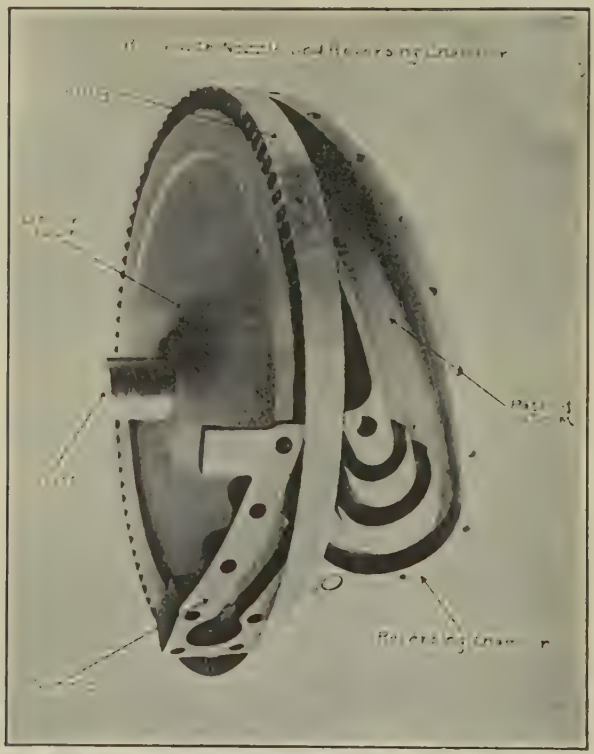


FIG. 366.— Steam inlet and reversing chamber of steam turbine.

arises from the fact that the direction cannot be reversed.

312. The Gas Engine. We have already learned that the gas engine is an *internal combustion* engine. Some vapor, usually from gasoline, benzol, or alcohol, is mixed with air and the mixture is exploded in the cylinder by an electric spark. The four-cycle engine is generally used in automobiles.

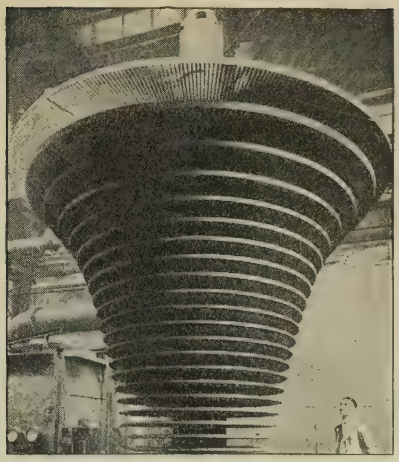


FIG. 366A. — There are 10,853 bucket blades on this 66,000 H.P. rotor. The blades vary in length from 1.5 in. to 30.5 in.

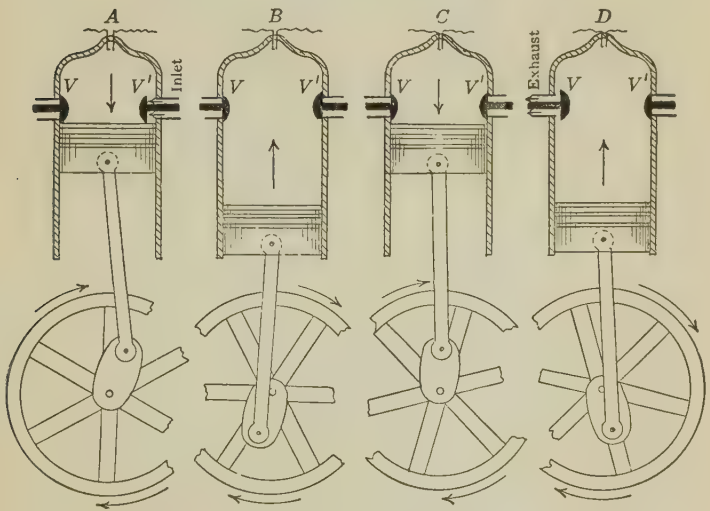


FIG. 367. — Four-cycle gas engine. *A*. Intake. *B*. Compression. *C*. Ignition. *D*. Exhaust.

Fig. 367 is used to represent the four cycles of a single cylinder. In starting the engine, we first pull the piston down, either by means of a crank attached to the crank shaft or by means of a self-starter which is geared with it. A partial vacuum is thus produced in the upper part of the cylinder above the piston, and the mixture of gasoline and air that is formed in the carburetor enters through valve V'. This is cycle one, or the *intake*. During the next half revolution of the crank shaft the piston moves upward. Since *both valves are closed*, the gas mixture is compressed to a small volume. Cycle two is the *compression* stroke. When the piston has reached the highest point, or nearly so, an electric spark is produced across the terminals of the spark plug which is screwed into the head of the cylinder. The gas explodes and drives the piston down with great force. Of course *both valves are closed* during this third cycle, which is the *working stroke* of the engine. During the fourth cycle, shown at D, the exhaust valve V is open to let the waste products of combustion escape as the piston again moves upward. Since force is applied to the piston during the third cycle only, the inertia of the flywheel must keep the piston moving during the other three cycles. To make a gas engine run more steadily, several cylinders are grouped and so arranged that the explosions will be consecutive. The opening and closing of the valves, as well as the timing of the spark, are all controlled by cams or eccentrics. Their action will be more fully explained in the chapter on the automobile.

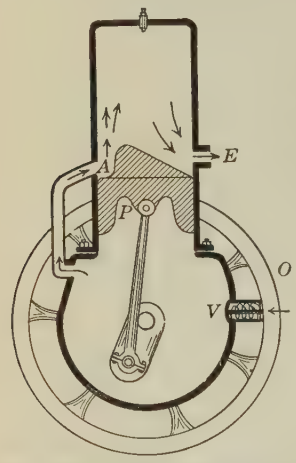


Fig. 368. — Two-cycle gas engine.

313. Two-cycle Engine. We have seen that the working stroke of a four-cycle gas engine comes once in two complete revolutions. With the two-cycle engine there is a working stroke every revolution. The crank shaft of this engine revolves in a gas-tight crank case. On the upstroke of the piston P a partial vacuum is produced in this air-tight case. (See Fig. 368.) An explosive mixture of gas and air is then drawn in through O as the valve V opens During the downstroke of the piston this mixture is compressed. When the piston reaches the point A, the ports at A and E are both

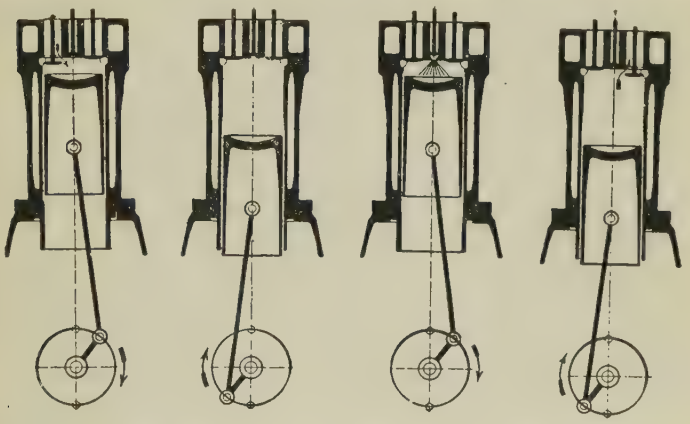


FIG. 369. — The four cycles of a Diesel engine.

open. The waste gases from the preceding explosion pass out at E, while the mixture which was compressed in the crank case flows through the by-pass and enters the cylinder at A. The next upstroke of the piston further compresses the gaseous mixture. The explosion occurs when the piston is near the top of the cylinder and the piston is driven downward during the working stroke.

The student will observe that the tightly fitting piston takes the place of valves as it closes the intake and exhaust ports. The incoming gas is deflected upward to prevent its

mixing with the exhaust gases. The absence of valves and valve mechanisms simplifies construction and makes the two-cycle engine cheaper to build than the four-cycle engine. It is not quite so efficient, however, since some of the unburned gases are lost through the exhaust. Two-cycle engines find use in motor-cycles, and for the operation of motor boats.

314. Diesel and Semi-Diesel Engines. Diesel engines were designed to use oils heavier and cheaper than gasoline.

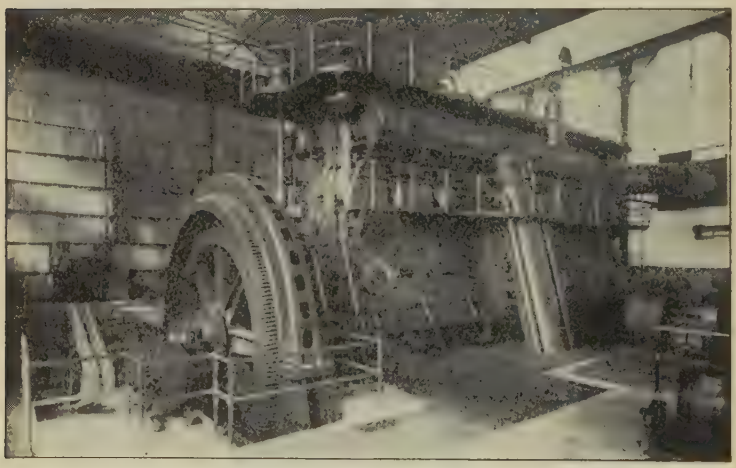


FIG. 370. — The 3750 H.P. Diesel engine installed for the Gas and Electric Light Company of Tucson, Arizona.

(See Fig. 369.) The compression of the mixture is carried further than with the gasoline engine, and the temperature thus produced rises high enough to enkindle the oil vapors. During the first cycle of the four-cycle Diesel engine pure air is drawn into the cylinder. The piston on its return stroke compresses this air to a pressure of more than 30 atmospheres. Just before the beginning of the third cycle, the fuel valve opens to admit the oil vapors, which are

forced into the cylinder by an air-blast of high compression. The vapors of the fuel oil are automatically ignited as they meet the red-hot compressed air in the cylinder. This is the power stroke of the engine. The waste gases are removed during the fourth cycle just as with the gasoline engine. No ignition system is necessary. (See Fig. 370.)

In the *semi-Diesel* engines the compression used is not quite so great. A firing pin is heated red hot and screwed into the end of the firing chamber in order to start these

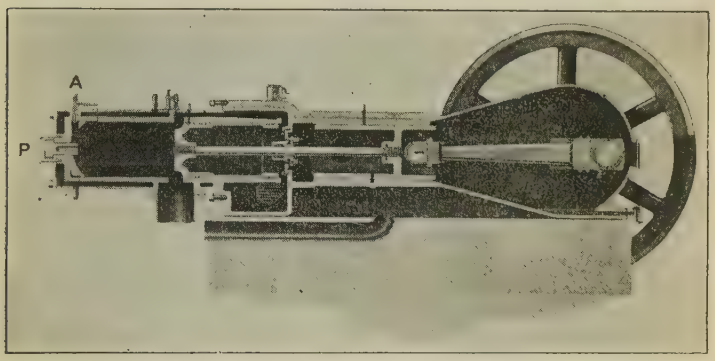


Fig. 371. — Semi-Diesel engine.

engines. In the four-cycle engine, air is admitted during the first stroke and compressed during the second stroke of the piston. Before the compression stroke is completed, the fuel oil is forced into the explosion head of the cylinder, where it vaporizes instantly as it strikes the heated walls. Water is often introduced to prevent premature explosion before the maximum compression is produced. In other respects this engine does not differ from the Diesel types.

Two-cycle engines of the Diesel and semi-Diesel types are in use. Excepting the automatic ignition, they are not very different from the two-cycle gasoline engines. Additional mechanism must be used to deliver the fuel under high pressure. In the two-cycle engine, Fig. 371, the oil is forced

into the cylinder at A under a pressure of 2600 lb. per sq. in. The oil is vaporized as it strikes the hot firing plug P.

315. Advantages and Disadvantages of the Gas Engine. The efficiency of the gas engine is about 25%, considerably

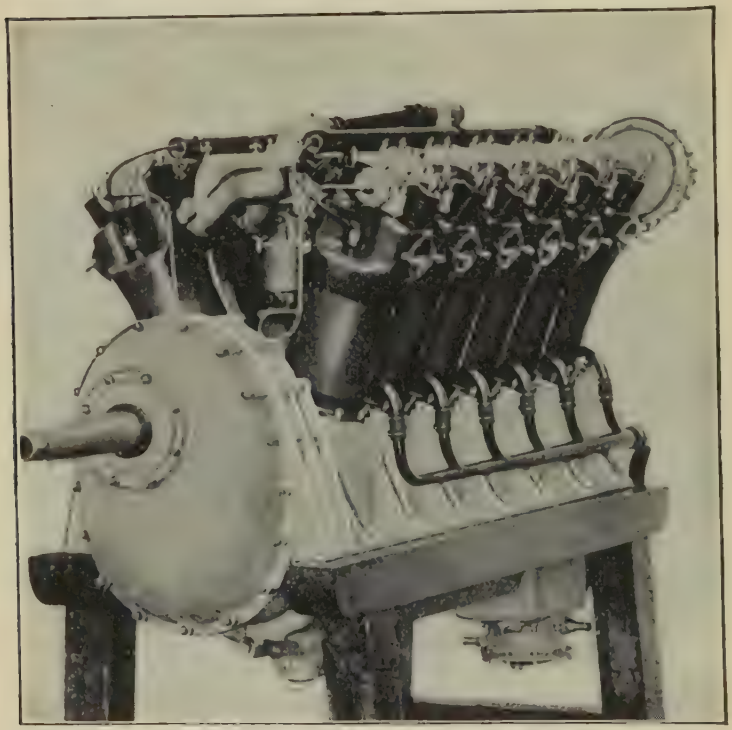


Fig. 372 — Liberty motor. This motor was developed by American engineers during the World War. It was used for the heavy bombing planes. The twelve cylinders are water cooled. At 1700 revolutions per minute, the motor develops 400 horse power. Since its weight is just over 800 lb., it yields 1 H.P. for 2 lb. of its weight.

higher than that of the steam engine. It is very compact and furnishes a high horse power for its size. The Liberty motor furnishes about 1 H.P. for 2 lb. of weight, Fig. 372. The fuel takes up very little room, but it is quite expensive.

Without the development of the gas engine the airplane would have been impossible. The gas engine may be started at a moment's notice, and it does not waste fuel when it is stopped. With the steam engine considerable time is required to produce steam, there is the trouble of stoking, and some fuel is always wasted when the engine is shut down. Fig. 373 shows the Wright whirlwind motor, a type used in the *Spirit of St. Louis.*

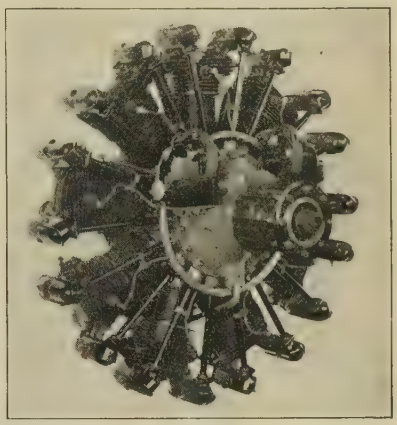


FIG. 373.— A Wright Whirlwind motor of the type used in the *Spirit of St. Louis.*

The gas engine is very sensitive. The spark must occur at just the right time. With a steam engine the speed may be varied at will by regulating the amount of steam entering the cylinder; it can also be readily reversed. The gas engine cannot be reversed. While the speed can be regulated to some extent by advancing or retarding the spark, or by controlling the gas supply, yet gears are necessary to secure the proper variation of speed. The gas engine cannot be run economically at low speeds. The gas engine is often noisy and the gases from the exhaust are disagreeable and poisonous.

SUMMARY

427 gm. meters of work are equivalent to one calorie of heat. One B.T.U. is equivalent to 778 ft. lb. of work.

Since heat may produce steam, and expanding steam produces pressure, the formation of steam furnishes one of the best methods of converting heat energy into work. The explosion of gasoline vapor is also much used for this purpose.

The ordinary steam engine uses from 7 to 20% of the total fuel energy. The gas engine is somewhat more efficient. The cam is used to change a reciprocating motion into a rotary one, and vice versa.

Steam engines are of two types: (a) reciprocating; (b) turbine. The four cycles of a gas engine are as follows: (1) Intake; (2) Compression; (3) Explosion; (4) Exhaust.

QUESTIONS

1. Would you expect the steam leaving the cylinder of a steam engine to have the same temperature as the steam which enters the cylinder? Explain.

2. Why is ocean water unsatisfactory for use in steam boilers?

3. Why is the temperature of the steam in a pressure boiler more than 100° C.?

4. In steam boilers the flame is sometimes sucked through tubes or flues surrounded by water. What advantage has such an arrangement?

5. Explain why it is difficult to start a gas engine under load.

6. Why is it necessary to make the second cylinder of a double-expansion engine larger than the first?

7. Why do we need more food in winter than in summer?

8. What is meant by "dead center" as applied to a steam engine?

PROBLEMS

1. A sled is drawn over the ice with a pull of 50 lb. How many B.T.U.'s will be produced by friction if the sled is drawn 10,000 ft.?

2. Under a boiler 2000 lb. of coal are burned per hour. If each pound of the coal yields 12,000 B.T.U.'s, what H.P. engine working at an efficiency of 15% can be operated by this boiler?

3. From what height must a block of ice fall to be melted by the heat of impact, assuming that 50% of the heat generated is absorbed by the ice?

4. How many B.T.U.'s of heat energy does a 175-lb. man lose in climbing a mountain 2000 ft. high?

5. The average pressure of steam in a steam engine is 140 lb.

per sq. in.; the diameter of the piston is 14 in., and the stroke is 24 in. How many ft. lb. of work are done at each stroke? At each revolution of the flywheel? If the flywheel makes 400 revolutions per minute, what is the horse power?

6. From a consideration of problem 5, what factors affect the horse power of a steam engine?

CHAPTER 14

SOUND

A. SOUND AND WAVE MOTION

Vocabulary

Microphone, a sensitive telephone transmitter.
Acoustic, pertaining to the science of sound or of hearing.
Resonance, the reinforcement of one sound wave by another.
Interference, the extinction or reduction of one sound wave by another.
Refraction, the bending of a sound wave out of its path as it enters a denser or rarer medium.

316. Source and Nature of Sound. If we pluck, strike, or bow a stretched string, it vibrates, or swings to and fro. When we hold a tuning fork and strike one of the prongs a sharp blow, the fork vibrates. Such vibration may be shown by holding the prongs of a tuning fork in a tumbler of water. (See Fig. 374.) Waves are set up in the water by the vibrating prongs. Fig. 375 may be used to show how matter that is struck, plucked, or bowed is actually caused to vibrate. As the vibrating body swings to and fro, it produces *sound waves.* Any matter, even air itself, may produce sound waves when it is caused to vibrate at a certain rate. Hence, *sound waves have their origin in vibrating matter.*

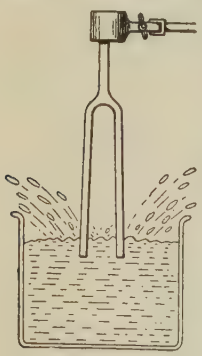


FIG. 374. — The vibrations of the fork disturb the water.

Before we can receive the sensation of sound, however, these sound waves must be conducted to the ear by some medium. In the majority of cases, sound waves come to us through the surrounding air. Fig. 376 shows how sound waves may be made to operate a signal.

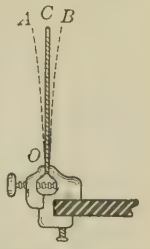


Fig. 375. — Vibrating body.

Our ears are well adapted to receive sound waves. The outer ear, Fig. 377, is so shaped that it collects sound waves and conducts them to the drum of the middle ear. The vibrations of this drum are amplified by the small bones of the ear, which act as small levers and multiply the impulse. In the inner ear the vibrations stimulate the auditory nerves and produce the sensation of sound.

In the *physiological* sense of the term, three things are essential for the production of sound: a vibrating body; some medium for transmitting the sound waves; and the

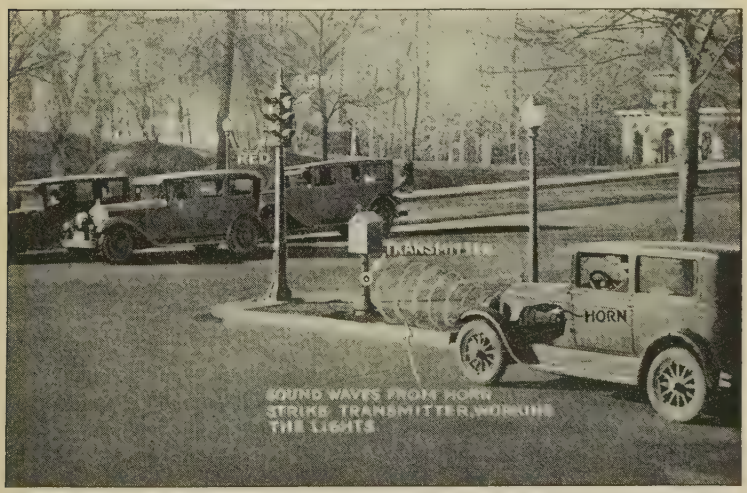


Fig. 376. — It has been proposed to use sound waves to operate signal lights. (*Courtesy of Popular Science Monthly.*)

ear, which serves as a receiver. In the *physical* use of the term, the word *sound* is synonymous with *sound wave*.

317. Media for Sound Transmission. When someone in the basement taps on a steampipe, the sound can be heard distinctly in the rooms above. This shows that the metal pipe transmits sound readily. A street-car can be heard at a

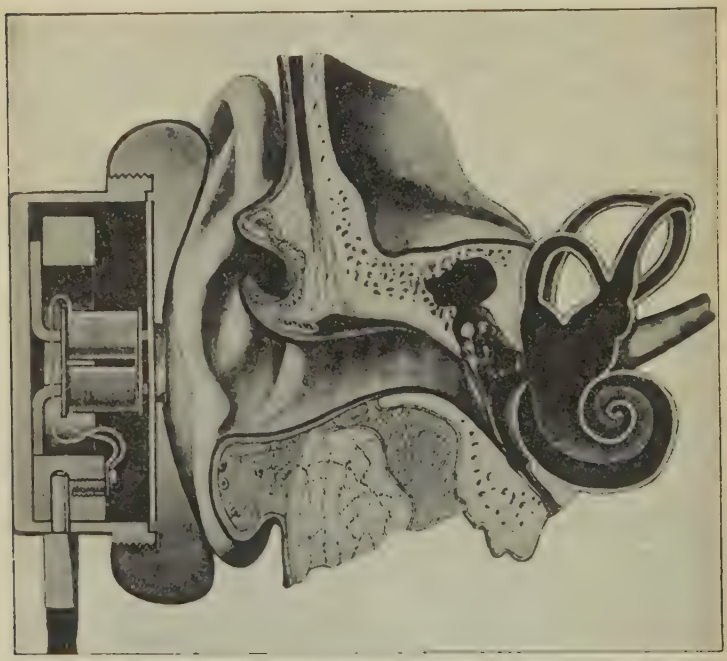


FIG. 377. — The sound waves from the receiver are transmitted to the inner ear. Note condensations in external ear. (*Courtesy of Bell Telephone Laboratories.*)

considerable distance by a person standing near a trolley pole, since the sound travels through the trolley wire and is then transmitted to the pole. Some persons who are partially deaf can tune a violin perfectly; since the chin rests on the instrument, the vibrations are transmitted through the

jaw-bone. A famous inventor, who is hard of hearing, is said to hear phonograph records distinctly by resting his head against the cabinet of the instrument so the vibrations may travel through the bones of the head. In general, *solids are better media for transmitting sound than either liquids or gases.*

On the other hand, we sprinkle sawdust on the floor to deaden the sound. Shoes with rubber soles do not produce much noise. Rugs help to prevent noise, and some floors are covered with cork-board. A silence cloth or a pad prevents the clatter of dishes on a dining room table. Such solids as cork, sawdust, cotton batting, rubber, and felt do not transmit sounds readily, either because they are porous, or because their elastic constant is low.

If the ear is held under water, the paddle-wheels of a steamer can be heard a long distance, much farther than when the sound waves come through the air. During the war, vessels were fitted with listening devices, or "ears," to detect the presence of hostile submarines. Fish are believed by fishermen to have very sensitive ears. They doubtless hear clearly sounds that have their origin in the water, but it is quite doubtful whether they hear many sounds coming from ordinary air, such as conversations between two persons. In general, liquids are poorer transmitters of sound than elastic solids, but they are better transmitters of sound than gases.

From everyday experience we know that gases transmit sounds quite readily. In fact, air is the most important medium for sound transmission. Rarefied gases do not transmit sound so well as dense gases. As one climbs a mountain, he must speak a little louder in order to be heard, because the air is less dense than that in the valley.

If we put a small alarm clock under a bell glass and begin to exhaust the air, the sound of the alarm will become fainter and fainter as we continue to pump air out of the bell glass.

If the clock is placed on layers of felt so the sound cannot travel through the solid base of the pump, the alarm will become almost inaudible as a vacuum is approached. Thus we are led to the conclusion that sound waves do not travel through a vacuum.

318. Velocity of Sound in Air. We often hear a thunderclap several seconds after the lightning flash. When a pistol is fired at a distance of several hundred feet, we see the flash a few seconds before we hear the report. Since for short distances light is practically instantaneous, we may assume that the interval between the flash and the report is the time required for the sound to travel the intervening distance.

The velocity of sound was determined by setting up cannon on hills several miles apart and firing them alternately. The distance between the two stations was measured, and the time required for the sound to travel that distance was carefully reckoned. By firing from the different positions, the errors due to the velocity of the wind were eliminated. The average of a large number of trials by these direct methods and also by indirect methods which have been used shows that *in air at 0° C. the velocity of sound is 1090 ft. per second.* As the temperature rises the velocity increases. The rate of increase is about *2 ft. per second for 1° C.* In the Metric system the velocity at 0° C. is 332 meters per second. The increase in velocity per degree is about 0.6 meter.

319. Sound Ranging. A very interesting illustration of how our exact knowledge of the velocity of sound can be put to practical use developed during the World War, when it was found possible to locate enemy field guns by the reports of their firing even when the flash was completely concealed. Listeners at a series of microphones scattered over an area behind the trenches recorded with great precision the exact time when the report of the gun was received

Suppose we let the points A, B, and C of Fig. 378 represent the positions of three listeners. The distances between them had all been accurately measured. B hears the report of a gun 1 second after A hears the same report, and C hears the report 2 seconds later than A. Just as water waves spread out in all directions from a pebble thrown into a pond, so the sound waves from the gun as a center spread out along the ground in ever-increasing circles. Assuming the velocity of sound to be 1120 ft. per second, we draw from B and C as centers two circles having radii whose relative lengths are 1120 (representing 1 second in time) and 2240 (representing 2 seconds in time) respectively. The arc drawn through A, which touches the circumferences of the two circles, is a portion of the circumference of the sound wave just as it reaches the listener at A. The center of this circle is the position of the gun. The accuracy of this method proved to be so exact that large guns several miles distant were located within a few feet, and destroyed by gun-fire.

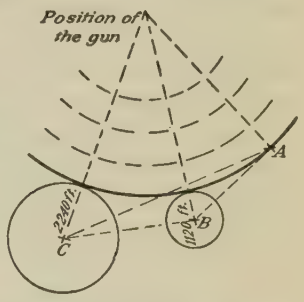


FIG. 378. — Sound waves are concentric.

320. Velocity of Sound in Other Media. In 1827 two Swiss scientists measured the velocity of sound in water. At one station a bell was rung under the water of Lake Geneva at the same time some powder was exploded at the surface. About 8 miles distant an observer counted by means of a stop watch the time between the observed flash and the sound which he received from an ear trumpet under the surface of the water. They found the velocity of sound in water to be 1435 meters or about 4700 ft. per second, a little more than four times the velocity in air. In steel the velocity of sound is more than 15 times as great as in air.

The velocity of sound in other media is given in Table 8 of Appendix C.

321. Vibration. If a steel strip is clamped at one end and struck a sharp blow with a hammer at its free end, it vibrates or moves to and fro, as shown in Fig. 375. Just as in the vibration of the pendulum (see § 149), the movement from A to B constitutes a *single* vibration; from A to B and return is a *complete* vibration. The *amplitude* of vibration is the angle AOC; the *period* is the time required for one complete vibration; and the *frequency* is the number of vibrations per second.

322. Kinds of Vibrations. If we fasten the ends of a spiral spring several feet long, and then pluck the stretched string at *right* angles to its length, as in Fig. 379A, a wave is set up which travels along the spring from one end to the other, and then returns by reflection. A wave that moves at right angles to the path along which it travels is *transverse*.

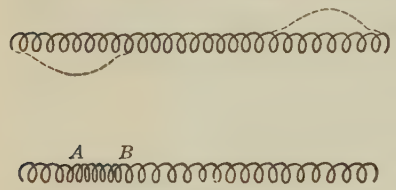


FIG. 379. — *A*. Transverse waves. *B*. Longitudinal waves.

On the other hand if we compress several turns along the spring as shown in Fig. 379B, and then release them quickly, a wave is produced that vibrates in the same direction as the path along which it travels. Such a vibration is *longitudinal*.

The water waves which are so familiar to students are transverse. As the wave advances, the water rises and falls but actually there is little or no forward movement of the water itself. That there is no progressive motion of matter in transverse waves is well illustrated by a field of waving grain. Before the wind, the stalks bend forward and downward; after the wind has passed, they bend upward and backward. Thus the wave travels across the field, but of course there is no progressive movement of the grain itself.

The length of a water wave is measured from a particle in one wave to a particle in the same phase of the next wave. In Fig. 380, the length may be measured from A to B, from C to D, or from x to y. The highest parts of the waves as shown at C and D are called *crests;* T is the *trough* of the wave.

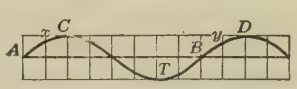


FIG. 380. — Transverse waves.

323. Sound Waves Are Longitudinal. Look at Fig. 375. While the steel strip there shown is moving from A to B, the air immediately in front of it is compressed or condensed, while the air immediately behind it is slightly expanded. As the strip moves back again from B to A, the air that was compressed by the first movement is expanded and the air that was expanded is compressed. As the strip continues to vibrate, it produces a series of *condensations* and *rarefactions,* which are illustrated in Fig. 381 where the crowded lines represent the condensations and the others the rarefactions. Such a *train of waves* is longitudinal; that is, they develop in the direction of the path along which the waves are traveling.

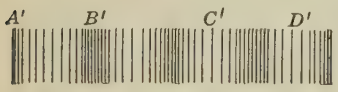


FIG. 381. — Train of waves.

There is little forward movement of the air, since each pulse communicates its energy to the air in front in much the same manner as with the collision balls of Fig. 382. If ball A is raised and then let fall, the impulse is communicated to each ball in turn, until C is reached. This ball then flies out to the position shown, the others remaining stationary.

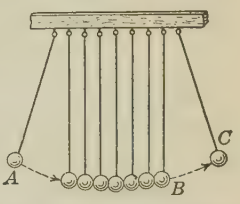


FIG. 382. — How waves progress.

The length of a sound wave is equal to the distance between successive condensations or successive rarefactions. In Fig. 381, the sound wave is measured from A' to B', or from C' to D'.

324. Relation between Velocity, Wave Length, and Vibration Rate. Suppose we have a fork which vibrates 275 times in one second, and suppose that the velocity of sound in air is 1100 ft. per second. It is evident that we will have 275 condensations per second, and that they will form a train of waves 1100 ft. long. By dividing 1100 ft. by 275, we find that each wave is 4 ft. in length. The first wave travels 4 ft. before the next one is produced; before the third vibration has started, the first one will be 8 ft. distant, and the second one will have traveled 4 ft.

Let us use the letter v to represent the velocity, l to represent the wave length, and n to represent the frequency, or the number of vibrations per second. Then, $v = nl$. If any two of these quantities are known, the third may be determined.

PROBLEM. A fork having a frequency of 320 has a wave length of 3.5 ft. Find the velocity of the sound in air. What was the temperature?

Solution. From the formula, $v = nl$, we see that the velocity is equal to the product of the frequency and the wave length. 320×3.5 ft. $= 1120$ ft., the velocity in feet per second. To find the temperature, we subtract 1090 ft., the velocity at 0° C. from 1120 ft. The difference is 30 ft. $30 \div 2 = 15$, the number of degrees needed to cause an increase of 30 ft. per second in the velocity. Hence the temperature was 15° C.

B. REFLECTION OF SOUND

325. Echoes. Everyone has stood at some distance from a cliff or forest and listened to the echo which is produced as he calls loudly. Just as a rubber ball rebounds from a hard surface, so sound waves are reflected when they strike against a medium of greater density. If the sound wave travels back along the perpendicular to the reflecting medium, a person in its path hears the sound repeated. *An echo is a repetition of a sound due to the reflection of the sound wave from some surface.* A person standing between parallel walls may

hear a sound repeated several times as the sound wave is reflected back and forth between the walls. A remarkable case of this kind occurred in a city in Indiana. The word "Knickerbocker," when uttered at one particular spot, was re-echoed twenty times before it became inaudible. The rolling of the thunder is caused by echoing and re-echoing as the sound wave is reflected from cloud to cloud, or from a cloud to the earth.

The reflected sound wave travels at the same velocity as the direct wave. On a day when the temperature is 20° C., the velocity of sound is 1130 ft. per second. A cliff 1130 ft. distant will produce an echo after 2 seconds. It will take one second for the direct wave to reach the cliff, and one second for the reflected wave to return.

326. How Echoes May be Useful. In foggy weather the captain of an ocean vessel may use echoes to determine his nearness to a rocky coast or an iceberg. If the blast of the whistle is returned quickly, he knows he is approaching danger. This method of sensing danger is not altogether depeı lable because weather conditions may make it hard to hear the echoes or judge the direction. Many vessels are also fitted to receive submarine signals, since an under-water signal is not affected by weather conditions. Iron tanks are fitted near the bow of the vessel, one on either side of the ship. Each tank, which is filled with salt water, contains a microphone which is connected with telephone receivers in the pilot house. A sound signal is produced, which is transmitted through the water to some distant object. Then it is reflected back to the ship where it is transmitted through the side of the ship to the microphone, which amplifies the sound in the receiver. Just as a person with two ears can determine the direction from which a sound comes, so the two receivers enable a listener to judge from what direction the signal is coming. The time elapsed enables him to calculate the distance.

The *depth of the water* may be determined in a similar manner. A sound produced from the hull of the vessel travels downward through the water and is reflected back from the bottom of the ocean. By measuring the time which elapses between the sending and the receiving of such a signal, the depth of the ocean can be calculated, since we know the velocity of sound in water. This method of finding the depth of water is rapidly replacing the line and lead formerly used for sounding.

327. Acoustic Properties of Buildings. In some large halls and assembly rooms, echoes prove troublesome. The duration of sound is about $\frac{1}{10}$ of a second. That means that the sensation of sound continues for $\frac{1}{10}$ of a second after the sound stops. If a sound wave is reflected from one wall of a room before the original sound dies out, confusion will result. To illustrate, suppose that sound has a velocity of 1100 ft. per second. In $\frac{1}{10}$ of a second the sound will travel 110 ft. If an assembly hall is just 55 ft. long, a sound uttered at one end will travel the length of the hall and back again in $\frac{1}{10}$ of a second. Such halls are difficult for speakers because the echoes are so troublesome. A trained speaker will so time his words and syllables that the echo does not produce confusion. Quite often the echoes disappear when the hall is filled with people, since the sound waves are broken up. Furniture and draperies are also helpful in breaking up sound waves and preventing troublesome echoes.

328. Whispering Galleries. Some large buildings have remarkable acoustic properties. Sometimes a dome-shaped ceiling will so reflect the sound waves that they are focussed at one particular place. In the Capitol building at Washington, whispers that are uttered near one side of the Hall of Statuary can be heard distinctly near the opposite side, although they are inaudible in the center of the room, only half as far away. A low whisper uttered near one side of St. Paul's Cathedral in London is distinctly audible at the other

side, over 100 ft. away. A pin dropped on a railing near one end of the Mormon Temple in Salt Lake City can be heard clearly at the other end, over 200 ft. distant.

329. Sound Waves Photographed. The series of photographs shown in Fig. 383 were taken by Professor A. L. Foley, of Indiana University. They show very clearly just how the actual sound waves behave. The origin of the sound wave was a spark produced between electric terminals. This wave spread out in all directions, forming larger and larger spheres as it advanced, in much the same way that a toy balloon increases in size as we inflate it. When the sound wave strikes a plane surface through which it cannot pass, the part of the wave farthest in advance strikes the reflector first and is turned back. The other portions are then reflected in turn, as shown at *D*. The reflected wave would represent the echo of the original sound. From a curved surface the sound wave is also reflected, but its curvature is increased as it is turned back from a convex surface, as in *B;* its curvature is decreased when it is turned back from a concave surface, as in *E*. Sound waves are refracted, or bent out of their course, in passing through a lens filled with some gas either denser or rarer than air. In *C* of the figure we see that both reflection and refraction occur, part of the wave passing through the lens, and a part being reflected.

C. LOUDNESS AND PITCH

330. Sound Characteristics. Some sounds are loud, others are soft and low; the chirp of a cricket is a shrill, high note, while the growl of a bull-dog is a deep bass; we enjoy hearing some persons sing, but unfortunately some other voices are not so pleasing. These three illustrations show how sounds may differ. Since they do not overlap, we must consider the following properties of sound as fundamental: (1.) *loudness*, or *intensity;* (2.) *pitch;* (3.) *quality.*

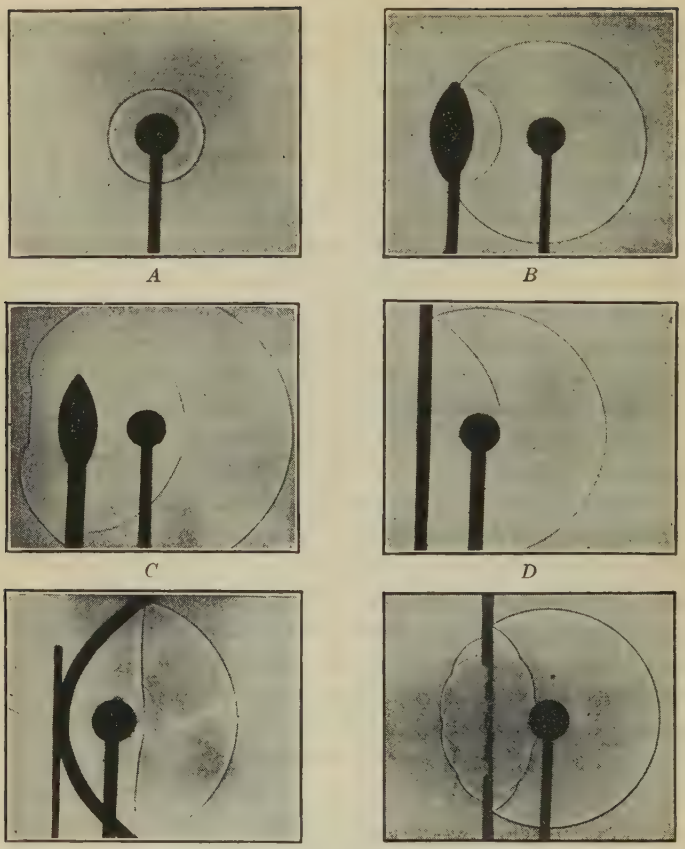


FIG. 383. — Photographs of sound waves taken by Professor A. L. Foley of Indiana University. *A*. Spherical sound wave taken 0.0001 sec. after the spark that produced the wave. *B*. Sound wave taken 0.00015 sec. after spark. Shows expanding wave and reflection from convex surface of a gas lens. *C*. Same wave 0.00023 sec. after spark. Shows original wave, reflected portion, and plane wave transmitted through gas lens. *D*. Spherical wave reflected from plane mirror. *E*. Sound wave reflected from parabolic mirror. Reflected wave is plane. *F*. Reflector is sheet of tin with four rectangular openings. Waves are reflected from five sections of tin, which have become new centers of disturbance. The waves passing through the openings are diffracted.

331. Intensity and Loudness. If we *throw* a small pebble into the water, higher waves are produced than by dropping it into the water more gently. When a bow is drawn across a violin string lightly, only a small amount of energy is imparted to the string, and the sound wave is not very *intense.* More vigorous bowing increases the *amplitude* and the sound becomes more intense.

A large stone thrown into a pond causes a larger volume of water waves than a small pebble. A large tuning fork

FIG. 384. — The amplifying horns make it possible for all the delegates at this National Convention to hear.

produces a greater volume of sound waves than a small one. Hence the large fork produces a more intense sound. A cannon produces a more intense sound than a toy pistol. From these observations, we conclude that the *intensity of sound is increased by increasing the amplitude and the area of the vibrating body.*

Sometimes *intense* sounds do not appear very *loud* to us. The medium through which they come may transmit sounds poorly, or we may be too far distant to hear them distinctly. We have already compared the different media through which sound waves are transmitted. Since sound waves are given off in all directions from a vibrating body, the waves spread out over a greater area as they advance. The areas of the surfaces of these concentric waves are proportional to the squares of their distances from the center. A bell will appear only one fourth as loud to a person one half mile away as it does to one who is only one fourth mile distant. We conclude that the *loudness of a sound is inversely proportional to the square of the distance from the source, and that it depends upon the medium through which the sound is traveling.*

332. Special Conditions Affect Loudness. As we have seen, sound waves ordinarily spread out in all directions from the vibrating body. But if one uses a *megaphone*, the sound wave to a large extent is directed by the sides of the megaphone and is intensified in one direction. In such cases doubling the distance does not decrease the loudness to one fourth for those persons directly in front of the megaphone. The same principle is used in the *phonograph horn* or the *automobile horn.* The *speaking tube*, which is used extensively in apartment houses, is similar to the megaphone in general principle. In some assembly halls, *sound reflectors* are used over the stage or platform to secure a better distribution of the sound waves to the different parts of the room. For large assembly halls, amplifying horns are extensively used. Fig. 384 shows how such horns were installed in one of the political convention halls. The microphone can be seen at the right.

In the *ear trumpet*, shown in Fig. 385, the principle of the megaphone is reversed. The larger end receives more of the sound wave and thus augments the sound by conducting

a larger volume of the sound wave to the ear. The mouthpiece of a telephone transmitter is similar in its application.

In the *stethoscope* as used by physicians a diaphragm much larger than the drum of the middle ear is used to increase loudness. Such a diaphragm collects more sound waves than the drum could possibly receive and transmits them by means of rubber tubes to the ears of the listener. The stethoscope was used in the dugouts during the war to listen for tunneling work preparatory to the placement of mines by the enemy.

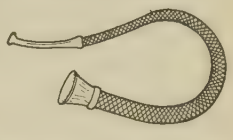


Fig. 385. — Ear trumpet.

333. Pitch. A piccolo may be as loud as a flute, but its note has a shriller pitch. A woman's voice has a higher pitch than that of a man, but it may not be as loud, or it may be louder. Pitch is not affected by loudness.

We may use a rotator and a siren disc to show that pitch depends upon vibration rate or frequency. The siren disc shown in Fig. 386 has four rows of holes, numbering 24, 30, 36, and 48 respectively, all regularly spaced. The holes in the inner row are irregularly spaced. If a stream of air is directed against the inner row of regularly spaced holes while the disc is rotated rapidly, a musical note is produced. The stream of air, in passing through the holes, is thrown into vibration. The number of pulses or vibrations per second must equal the product of the number of holes times the number of revolutions per second. If the speed is increased, the pitch rises. If we keep the speed constant and direct the stream of air against the outer row of holes, a note an octave higher is produced. If streams of air are directed

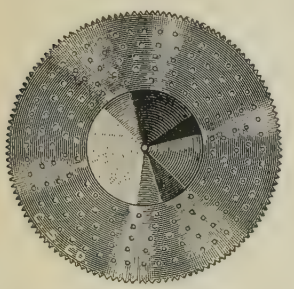


Fig. 386. — Siren disc.

against each of the holes successively, the notes *do*, *mi*, *sol*, *do'* are produced. From this experiment, we must conclude that the *pitch of a tone depends upon the number of vibrations that reach the ear per second.* The vocal cords of a woman singing the note C', are vibrating twice as fast as those of a man who sings a note an octave lower in pitch.

Since $v = nl$ (see § 324), it is evident that an increase in n, or the number of vibrations, must cause a corresponding decrease in l, the wave length. The wave length of a fork vibrating 512 times per second is just half the wave length of a fork that is vibrating only 256 times per second. *The pitch of the former is higher because twice as many wave lengths reach the ear per second.*

If a stream of air is directed against the row of irregularly spaced holes, the vibrations are irregular, and a jarring noise is produced. This is one of the distinctions between noise and music; in music, the pulses reach the ear in regular succession. Striking the desk with a stick, scraping the feet over the floor, or dropping the dinner dishes will set up irregular vibrations. The sounds produce noise, but not music.

334. Doppler's Principle. When the distance between the ear and a vibrating body does not change, the number of pulses reaching the ear per second is exactly equal to the frequency of vibration. If we are moving toward the vibrating body or if it is approaching us, we will then receive more pulses per second than the vibrating body is producing. For this reason, the whistle of a rapidly *approaching* train *rises* in pitch. As the train *recedes*, the pitch *falls*.

Suppose the velocity of sound is 1140 ft. per second, and the whistle has a frequency of 300 vibrations per second. The length of the sound wave is 1140 ft. $\div$ 300, or 3.8 ft. If the train is moving at a velocity of 45 miles per hour, or 66 ft. per second, it will be $66 \div 3.8$, or 17.3 wave lengths nearer the listener at the end of one second. Hence the listener receives 17.3 more pulses per second than the whistle

produces. The new pitch corresponds to 317.3 vibrations per second, instead of 300. As the train recedes, 17.3 pulses per second are subtracted from the normal vibration rate, and the pitch falls to 282.7 vibrations per second. Such a rise in pitch when a sounding body approaches, or fall in pitch when it recedes, is known as Doppler's principle.

D. RESONANCE AND INTERFERENCE

335. Forced Vibrations. A tuning fork vibrating freely has a natural vibration rate which depends upon its length, thickness, and the material of which it is made. The strings of a musical instrument also have natural vibration rates free from external influences except gravity and friction. It is possible, however, for one vibrating object to impress its vibration rate upon another that has a different natural frequency. When we hold the stem of a vibrating tuning fork against a table, the tuning fork impresses its vibration rate upon the table. Energy is transmitted through the stem of the fork, and the table is *forced to vibrate* in response to the periodic force thus applied. A thin string stretched from one post to another does not produce a very intense sound when it vibrates. When the same string is stretched across the bridge of a violin, the thin wood of which the violin is composed is forced to vibrate in response to the vibrations of the string. The intensity of the sound is increased by the *forced vibrations* of the instrument. The sounding board of a piano is another example of forced vibrations used to intensify sound.

336. Sympathetic Vibrations. Suppose we have given two mounted tuning forks, Fig. 387, both having the same vibration rate. We may let a pupil near the rear of the room hold one fork near his ear while some one at the front of the room strikes the other fork a sharp blow to throw it into vibration. After a few moments, the prongs of the latter fork may be touched to stop its vibrating. The pupil at the rear of the

room will discover that the fork which he holds is now vibrating feebly. The impacts of the sound waves from the first fork fell upon the second fork in regular succession and caused it to vibrate sympathetically. The strings of a violin may be heard vibrating softly when a person playing a piano in the same room strikes notes which have the same pitch as that which the strings could produce. *Sympathetic vibrations* occur when the natural vibration rates of two objects are the same, or when the vibration rate of one of them is a multiple of the other. If we change the natural vibration rate of one fork by adding a weight to one of its prongs and then repeat the experiment, no sympathetic vibrations are produced. Both forks must have the same frequency. The principle of tuning a radio set is not essentially different from sympathetic vibrations.

Fig. 387. — Resonant forks.

337. Resonance. Let us hold a vibrating tuning fork over a cylindrical tube partly filled with water. Now, if we pour water into the tube gradually, it is possible to find a point where the sound wave which is reflected back from the water surface unites with the direct wave from the fork and reinforces the sound. If we pile the crest of one water wave upon the crest of another wave, the resulting wave will be higher. In a similar manner, if we make the tube of such length that a condensation reflected from the water meets another condensation set up by the fork, the sound wave will be louder. A tube so adjusted that it will reinforce sound waves is called a *resonator*.

In Fig. 388, suppose we consider what happens while the prong *c* moves from *a* to *b* and back in making a complete vibration. If we are to have resonance, the sound wave must travel down the tube and back while the prong is making a *single* vibration from *a* to *b*. Under such conditions the condensation will return in time to meet the next condensation, started as the prong *c* begins to move from *b* to *a*. While the prong, *c* is making a *complete* vibration, the sound wave will travel four times the length of the tube, down and back twice. We may define *resonance as the reinforcement of sound by the union of the direct and reflected sound waves.* From the experiment just studied, we find that *a closed tube whose length is one fourth the wave length of the fork produces the best possible resonance.* The length of the closed tube, *l'*, equals one fourth the wave length, *l*.

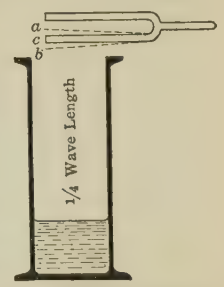


FIG. 388. — Resonance by closed tubes.

Wave length = 4 (length of closed tube).

When a vibrating fork is held over an *open* tube, resonance is also produced. Experiment shows, however, that such a tube produces the *best resonance when its length is just one half the wave length of the fork.* With an open tube, the condensation spreads out when it reaches the end of the tube, and a condensation is returned as a rarefaction.

338. Interference. Suppose we repeat the experiment of the preceding section. We find that resonance is produced in a closed tube which is one fourth the wave length of the fork. Now let us continue to add water to the tube until the air column is just $\frac{1}{8}$ the wave length of the fork. In such a case the condensation of the *reflected* wave meets a rarefaction of the *direct* wave. This reduces the sound wave or extinguishes it entirely. The reflected wave *interferes* with the

direct wave. It is easy to imagine that the crest of one water wave might entirely fill the trough of another water wave if the two should coincide. Such a condition would destroy the wave and make the surface level. We may also have interference between two sound waves traveling through a medium in the same direction, provided a condensation of one wave coincides with a rarefaction of the other. When one sound wave is so super-imposed upon another that *silence* is produced, we have *interference.*

339. Beats. Let us use Fig. 389 to represent sound waves of unequal length traveling in the same direction through the air or some other medium. The heavy line in *A* represents a wave 4 ft. long, and the dotted line a wave 5 ft. in length, both coming from the point *X*. We observe that at some places the two waves coincide in almost the same phase and at other places in opposite phase. From a straight line in *B* which is used to represent the level, we may plot a *composite* curve constructed by using the *resultant* of the crests and troughs of the two trains of waves. At *C* the crests which represent condensations meet and the *sound is intensified;* at *D* a condensation coincides with a rarefaction, and the *sound is diminished,* or silence may result. When two tuning forks of different vibration rate are sounded simultaneously, the sound will be alternately augmented and diminished. *An outburst of sound followed by an interval of comparative silence is called a beat.* The number of beats per second is equal to the difference between the vibration rates of the two vibrating bodies. For example, a tuning fork having a frequency of 256 will produce 4 beats per second if sounded with a fork whose frequency is 260, or with one whose vibration rate is 252.

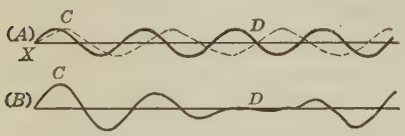


Fig. 389. — Interference.

SUMMARY

Sound has its origin in a vibrating body. Sound waves are transmitted to the ear through some medium. Solids are the best media for sound transmission; liquids and gases follow in the order named. Sounds do not travel through a vacuum.

The velocity of sound in air at 0° C. is 1090 ft. per sec. The velocity increases 2 ft. for a rise in temperature of 1° C.

Sound waves may be reflected, producing echoes. When the reflected sound wave reinforces the direct wave, resonance is produced. The best resonant length for a closed pipe is $\frac{1}{4}$ the wave length; the best resonant length for an open pipe is $\frac{1}{2}$ the wave length. Parallel walls often produce multiple echoes.

When two sound waves are so superimposed that a condensation meets a rarefaction, the sound is reduced by interference. An outburst of sound followed by an interval of comparative silence is termed a beat.

Sounds differ in loudness, pitch, and quality. Pitch depends only upon the number of vibrations that reach the ear per second. Loudness depends upon the amplitude of vibration, the area of the vibrating body, and the distance from the source of sound.

QUESTIONS

1. Do sounds of different pitch travel with the same velocity? Give a reason for your answer.

2. A person standing near one end of a long iron pipe hears two distinct sounds when the other end is struck with a hammer. Explain.

3. Why does the pitch of a circular saw fall as a board is pushed into the saw?

4. Why is it difficult for one speaking in the open air to be heard?

5. At a track-meet should the timers start their watches with the flash of the pistol or with its report? Give a reason for your answer.

6. When calling to some one at a considerable distance, is "cupping" the hands before the mouth of any advantage? Explain?

7. How may echoes be of use to vessels at sea during a heavy fog?

8. How do you account for the peculiar shape of the ceilings in the waiting rooms of many railroad stations?

9. Why was it so difficult for men to cut the barbed-wire entanglements in "no man's land" without being heard by the enemy?

10. Why is it difficult for the men in the rear of a long line of soldiers to keep in time with a band in front?

11. A little dog trotting across a bridge causes it to vibrate more vigorously than a team of horses walking and drawing a heavy load. Explain.

12. Why are soldiers commanded to break step when crossing a long bridge?

13. A few years ago a dancing floor collapsed when a number of couples were dancing the Charleston. What condition may have caused the collapse?

14. Deaf children listen to music by resting their hands and heads upon the frame of a piano? Explain.

15. How can an auto-mechanic use a stethoscope to good advantage?

16. Why does the pitch rise as water is poured into a tall cylinder?

17. How does a piano tuner use beats in tuning a piano?

18. Explain why the echoes produced in an empty hall usually disappear when the hall is filled with people?

PROBLEMS

1. A man counts 12 seconds between the flash of lightning and the thunder crash when the temperature is 22° C. How far away did the electrical discharge occur?

2. Three seconds elapse between the firing of a gun and the return of the report. How far away is the reflecting surface, if the temperature is 20° C.?

3. A man sets his watch by a whistle which is 2 mi. distant. If the temperature is 20° C., how much will his watch be in error? Will it be too fast or too slow? If the wind is blowing with a velocity of 30 ft. per second, how will the result be affected?

4. If sound travels 1 mile in 4.8 sec., what is the temperature of the air through which it is transmitted?

5. A fork that makes 384 vibrations per second produces resonance with a closed tube 8.9 in. long. Find the velocity of sound. What is the approximate temperature?

6. When the temperature is 25° C., a fork vibrates 64 times per second. What is the wave length produced?

7. Two forks have vibration rates of 320 and 384 respectively. How many beats per second are produced?

8. Two forks have vibration rates of 256 and 266 respectively. How many beats are heard when they are sounded simultaneously? A rubber band is placed around the prong of one of the forks, and then 15 beats per second are heard. Which fork was weighted to produce this result?

9. A closed tube is 30 cm. long. It produces resonance with a tuning fork when the temperature is 25° C. What is the wave length of the fork? What is its frequency?

10. A man drops a stone into a mine 1200 ft. deep. If the temperature is 15° C., how much time will elapse before he hears the stone strike the bottom? (Calculate both the time needed for the stone to fall and for the sound to return.)

11. A fork vibrates 256 times per second. If the temperature is 30° C., how long a closed tube will be needed to produce resonance with the fork?

CHAPTER 15

SOUND—MUSIC

A. MUSIC AND QUALITY

Vocabulary

Chromatic, colored; shades of tone analogous to shades of color.
Overtone, a note whose vibration is a whole number multiple of that of its fundamental.
Orthophonic (*orthos*, straight; *phonein*, to sound), reproducing more nearly the quality of the original.

340. The Diatonic Scale. In § 333 we used a siren disc and forced air through each of the four rows of holes *successively*. If we use the disc again and *simultaneously* force the air through all the rows of holes except the inner one, the four notes that are produced will form a major chord. The relative frequencies of the four notes will be 24, 30, 36, and 48. If we divide each of these numbers by six, we have the simple ratios 4, 5, 6, and 8. Any three notes whose vibration ratios are 4, 5, and 6 will produce a *major triad* when they are sounded together. These three notes, with the octave above the first note, produce a *major chord.* The *major* diatonic scale is built up of three major chords:

Syllables	do	re	mi	fa	sol	la	si	do	re
Letters	C	D	E	F	G	A	B	C′	D′
Vibration rates	256	288	320	341	384	426	480	512	576
Relative vibration rates	24	27	30	32	36	40	45	48	54
Chord (tonic)	4		5		6			8	
Chord (dominant)					4		5		6
Chord (subdominant)				4		5		6	

If we use 256 vibrations to represent middle C on the piano, then the table shows the vibration rates for the white

keys in a little more than one octave. We find that the vibration rates for C, E, G, and C′ have ratios of 4, 5, 6, and 8. They form a major chord. Another major chord is formed by the notes G, B, D′, and G′, and a third by the notes F, A, C′, and F′.

The note C′, which is one octave above middle C, has a vibration rate just twice as great as that of C. The frequency of a note an octave above another is always twice the frequency of the note of lower pitch. Doubling the frequency raises the pitch one octave. From the table, we see that the frequency of D is $\frac{288}{256}$, or $\frac{9}{8}$ times that of C. Of course D in this table is just $\frac{1}{2}$ the frequency of D′, an octave higher. The vibration rate of E is $\frac{320}{256}$ of C, or $\frac{5}{4}$; F is $\frac{341}{256}$, or $\frac{4}{3}$; G is $\frac{384}{256}$, or $\frac{3}{2}$; A is $\frac{426}{256}$, or $\frac{5}{3}$; and B is $\frac{480}{256}$, or $\frac{15}{8}$. C′ is $\frac{512}{256}$, or $\frac{2}{1}$. (See Fig. 390.)

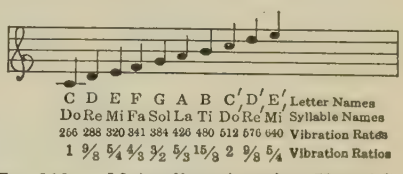

C D E F G A B C′ D′ E′ Letter Names
Do Re Mi Fa Sol La Ti Do Re Mi Syllable Names
256 288 320 341 384 426 480 512 576 640 Vibration Rates
1 9/8 5/4 4/3 3/2 5/3 15/8 2 9/8 5/4 Vibration Ratios

FIG. 390. — Major diatonic scale. Key of C.

In the next octave, we find that D′ is $\frac{9}{8}$ times the frequency of C′, the first note in the octave, or the key-note. ($\frac{576}{512}=\frac{9}{8}$). In the same manner we can find the frequency of any note in this octave by multiplying the vibration rate of the key-note by the ratios just given. For example, the frequency of E′ equals $\frac{5}{4}\times 512$, or 640. We could also find the vibration rate of E′ by doubling the vibration rate of E (320).

341. The Chromatic Scale. Suppose we use D as the key-note and multiply its frequency (288) by $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$ and 2 in turn. The table given below shows the results obtained when compared with the notes of the key of C.

	C	D	E	F	G	A	B	C′	D′
Key of C . .	256	288	320	341	384	426	480	512	576
Key of D . .		288	324	360	384	432	480	540	576

We observe that there is considerable variation, especially in the vibration rates of F and C′. The difference is so great that two new notes, F♯ (F sharp) and C♯, are used by the musician when he plays in the key of D. The notes E and A are not exactly the same, but no new notes are added here.

The vibration rate of F sharp, or F♯, is obtained by multiplying the frequency of F by $\frac{25}{24}$; if a note in the chromatic scale is to be flatted, its frequency is $\frac{24}{25}$ that of the note itself. These intervals are called *chromatic semitones*. They are represented by the black keys on the piano. By using different letters as key-notes, we find that five new notes, called flats or sharps, must be added to each octave.

342. The Tempered Scale. In building up the chromatic scale, we learned that five new notes must be added to the diatonic scale in each octave. If we examine the two scales shown above, keys of C and D, we note that there is a difference of 4 vibrations for the note E and about 6 for the note A. If all the possible keys were built up in the same manner and new notes added where any difference exists, a large number of additions would be needed. The black keys on the piano are used either as the sharp of the note below or as the flat of the note above. In the chromatic scale there is a difference between C♯ and D♭ (D flat). For example, $\frac{25}{24}$ times 256 equals 266 vibrations, or C♯; and $\frac{24}{25}$ of 288 equals 276 vibrations, or D♭. Putting in new notes with their sharps and flats wherever even slight variations occur would give an octave of about 70 notes. The difficulty in learning to play a piano or organ having 70 notes in each octave is obvious; it is so impractical that a system of equal temperament has been devised. It is a compromise scale. There are twelve *intervals* in the octave, including sharps and flats, and the vibration rate of C′ is just twice that of C. By extracting the twelfth root of 2, we get an equal interval for each semitone.

$$\sqrt[12]{2} = 1.05946.$$

In the tempered scale the vibration rate of any note can be obtained by multiplying the frequency of the preceding note by 1.05946. The equally tempered scale is used in playing most musical instruments. A skillful violinist, however, may produce better music by using the true intervals of the diatonic scale. A comparison of the two scales is shown in Fig. 391. The difference is not very great in any case. In fact few persons can tell a difference in pitch of only 2 or 3 vibrations per second.

Chromatic Scale		Tempered Scale	
C	256	C	256
C♯	266.6	C♯ or D♭	271.2
D♭	276.5		
D	288	D	287.3
D♯	300	D♯ or E♭	304.4
E♭	307.2		
E	320	E	322.5
F	341.3	F	341.7
F♯	355.5	F♯ or G♭	332
G♭	368.6		
G	384	G	383.6
G♯	400	G♯ or A♭	406.4
A♭	409.5		
A	426.6	A	430.5
A♯	444.4	A♯ or B♭	456.1
B♭	460.8		
B	480	B	483.3
C′	512	C′	512

Fig. 391. — Comparison of scales.

343. Standard Pitch. The middle C tuning forks that are used in all physical laboratories are all tuned to 256 vibrations per second. This gives A 427 vibrations per second. In *concert* pitch, which is now little used, middle C has 271 vibrations per second. *International* pitch differs slightly from that used by physicists in the diatonic scale, since A

equals 435 vibrations per second. With the pitch adopted by the American Federation of Musicians, A has 440 vibrations per second. Sopranos find it difficult to sing music written by Handel and his contemporaries when accompanied by instruments tuned to the pitch adopted by the American Federation of Musicians.

344. Harmony and Discord. Connect two jet tubes to the gas-cock. (See Fig. 392.) Support two glass tubes about 1 in. in diameter and 16 to 18 in. long over the jet tubes. Adjust the height of the flames properly and a singing noise will be produced. Now if the tubes are made unequal in length by means of a sliding paper cylinder, beats will be produced. When there are only a few beats per second, the sound is not displeasing. It is possible so to adjust the lengths of the tubes that a jarring, discordant noise may be heard; this occurs when the number of beats increases to about 30 per second.

FIG. 392.—Beats produced by singing flames.

If two or more notes are pleasing when sounded together, they are said to produce *harmony*. From the experiment we learn that the effect produced depends upon the number of beats per second. If the number of beats is 60 or more, they are so close together that the ear does not distinguish between them, and harmony is produced. The *maximum discord* occurs when there are about 30 beats per second.

345. Limits of Audibility. If the number of vibrations is fewer than 16 per second, the waves set up do not affect the auditory nerve, and no sound is heard. When we wave our arms, for instance, no sound is produced. The vibration rate of the lowest note on a piano is 27. It is said that the ears of some persons are not sensitive to this note. A note of very low pitch may be produced by pressing the forefingers against the ear, and then closing the other fingers

firmly. On the other hand the vibrations may be so rapid that the ear is not affected. The frequency at which this occurs varies with the individual, but the maximum vibration rate capable of being perceived by the ear appears to vary from 38,000 to 40,000 per second. The shrill chirp of the cricket is inaudible to some persons, because the vibrations are so very rapid. Loudness has nothing to do with such cases. The auditory nerves of such persons do not seem to be tuned to receive notes of very high or very low pitch, just as some eyes are not sensitive to certain colors.

In radio we use the term *audio-frequency* when we refer to vibration rates that are capable of affecting the ear. Frequencies below 10,000 per second are spoken of as audio-frequencies, because they are audible in a telephone receiver.

346. The Fundamental. Under certain conditions it is possible to see the vibrations of strings. Thus we find that a string may vibrate as a *whole*, as shown in Fig. 393. Strings may also vibrate in several parts or segments, with *nodes*, or places of no vibration, between the segments. (See Fig. 394.) Stranger still, it is possible for a string to vibrate as a whole and in parts at the same time, as represented in Fig. 395. In the laboratory for testing the vibration rate of strings, we use a *sonometer* which consists of strings which are stretched over a sounding board. When a string vibrates as a whole, it produces a note of its lowest possible pitch. Such a note is called its *fundamental.* When a stretched string is plucked, struck, or bowed in the middle, the string vibrates as a whole and sounds its fundamental.

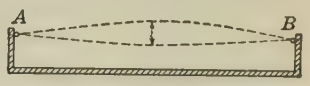


FIG. 393. — String vibrating as a whole sounds fundamental.

FIG. 394. — Loops and nodes.

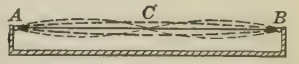


FIG. 395. — Overtones are produced by strings vibrating in parts.

347. Overtones. Suppose we divide a sonometer string into eight equal parts and put V-shaped paper riders on the string in the positions shown at 1, 2, 3, 4, and 5, Fig. 396. If we touch the string at C and bow it at D, the riders at the positions 1, 3, and 5 will be thrown off. Those at 2 and 4 are not disturbed. This proves that the string is now vibrating in four equal parts. That portion of the string included between A and B, Fig. 394, is called a *loop* or *segment*. The points where no vibration occurs are called *nodes*.

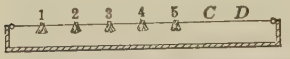


FIG. 396. — String vibrating in segments.

One of the most interesting things about this experiment arises from the fact that the pitch of the vibrating segment is two octaves higher than that of the fundamental. The new note is called an *overtone*. *A note whose vibration rate is a whole number multiple of that of the fundamental is called an overtone*, or *harmonic*. When a string vibrates in two segments, the overtone produced is an octave above the fundamental. For example, the first overtone of a C string is C′, a note of just double the vibration rate of C. ($256 \times 2 = 512$.) The second overtone of C has a frequency three times that of C. $256 \times 3 = 768$. A note having 768 vibrations per second corresponds to G′. The third overtone of C has four times its frequency. $256 \times 4 = 1024$, the note C″. The fourth overtone of C is E″, whose vibration rate is 1280. (256×5.)

348. Quality. It is quite easy to pick out the various instruments in an orchestra, even when the pitch is the same. Two persons may be singing true to pitch, but the voice of one of them may be more pleasing. We say the *quality* differs. The difference in quality may be demonstrated by bowing a string near the middle. While it is vibrating as a whole and sounding its fundamental, let us touch the string very *lightly* at the middle. The string continues to vibrate, but it now produces a richer and fuller tone. We have added

to the fundamental its first overtone and thus improved the quality. *The quality of a sound depends upon the number of overtones present and upon their prominence.*

When a string is plucked or bowed near one end, it always vibrates as a whole and in segments at the same time, as shown in Fig. 395. This produces overtones which blend with the fundamental and produce richer and fuller tones. In musical instruments, strings are not plucked, or bowed, or struck in the middle, but near one end to improve the quality.

Certain overtones are displeasing to the ear, since they produce notes that do not correspond to the musical scale. The sixth overtone is especially displeasing. Hence pianos are so constructed that the hammers strike the strings about $\frac{1}{7}$ of their length from the end. Then the string cannot vibrate in seven segments and produce the sixth overtone, which would be discordant.

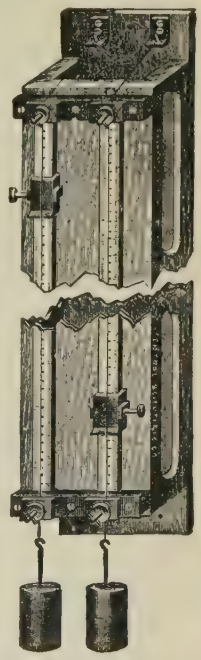


Fig. 397. — Sonometer.

B. LAWS OF STRINGS

349. Laws Governing the Vibration of Strings. If we examine a piano, we find that the bass strings are longer, thicker, and looser than those of the treble. Their density is also made greater by winding them with copper wire. We must bear in mind that the bass string has a low frequency, and the treble string vibrates rapidly. In the construction of the piano we have examples of all the methods used to control the frequency of strings. The sonometer, Fig. 397, may be used to study the vibration rate of strings. By its use several

facts concerning frequencies have been determined. The laws of strings may be stated as follows:

1. *Law of lengths.* When we wish to increase the pitch of any stringed instrument, we may shorten the length of the string. A violinist shortens the A string of his violin about one inch when he wishes to produce the note B. *The vibration rate of a string is inversely proportional to its length,* if its diameter, density, and tension remain unchanged.

Problem. If the D string of a violin is 12 in. long, how much must it be shortened to produce the note E?

Solution. D corresponds to 288 vibrations per second and E has a frequency of 320. Then, $288 : 320 = x : 12$. Therefore, $x = 10.8$ in., the length of a string which vibrates 320 times per second. The D string must be shortened 1.2 in. to produce the note E.

2. *Law of diameters.* On a guitar or harp, the strings that produce the notes of higher pitch are of smaller diameter. This is true of other stringed instruments. A string 0.1 in. in diameter will vibrate just twice as fast as a similar string 0.2 in. in diameter. *The vibration rate of a string is inversely proportional to its diameter,* provided its length, density, and tension are constant.

3. *Law of tensions.* When one tunes a violin or other stringed instrument, he tightens the strings to increase the frequency. It has been proved by experiment that *the vibration rate of a string is directly proportional to the square root of the tension on the string,* provided all other factors are constant.

Problem. A string stretched with a force of 9 lb. produces the note C; with what force would the same string have to be stretched to produce the note C′?

Solution. C has a frequency of 256, and C′ a frequency of 512. Then, $256 : 512 = \sqrt{9} : \sqrt{x}$. Whence, $x =$ equals 36 lb.

4. *Law of densities.* The heavier a string is, the more slowly it vibrates. For this reason some strings are made of

dense material, and other strings are wound with dense material to make the strings vibrate slowly. *The frequency of a vibrating string is inversely proportional to the square root of its density, if other factors are constant.*

B. MUSICAL INSTRUMENTS

350. Stringed Instruments. In a very large number of musical instruments the sound waves come from vibrating strings. The piano, violin, guitar, ukulele, mandolin, and harp are common examples. In each case some form of sounding board is used. The thin string does not have sufficient area to furnish the required volume of sound, but it forces the sounding board into vibration, even if their natural vibration rates are unequal. Thus the sound is intensified. Pairs of strings are used for certain octaves of the piano to give greater volume; in the treble, three strings are used for each note.

351. Organ Pipes. In some organ pipes a stream of air is directed against one edge of an opening, as in Fig. 398. A vibrating air-jet is thus produced. The frequency depends upon the length of the pipe, since the vibration rate is influenced by the return of the reflected air pulses. *A closed organ pipe is one fourth as long as the sound wave it produces. An open pipe is one half as long as the sound wave it produces.* To construct a set of organ pipes, their lengths must be made inversely proportional to the vibration ratios given in § 340. The pipes used for one octave, beginning with C, would have lengths of the following ratios: 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, and $\frac{1}{2}$. To summarize, the *pitch of a pipe varies inversely as its length. An open pipe produces a note an octave higher than a closed pipe of the same length.*

FIG. 398. — Organ pipes.

352. Overtones in Pipes. When a pipe is blown gently, it usually sounds its fundamental. If one blows harder, it is possible to produce overtones. In such cases the air column vibrates in loops. In a *closed* pipe there is always a node at the closed end and a loop or anti-node at the other end. The only overtones possible in such a pipe are those whose vibration rates are *odd* multiples of the fundamental. The first overtone of a closed C organ pipe is not C′, but G′, a note whose frequency is 3 (an odd number) times that of the

Fig. 399. — Clarinet.

fundamental. The next overtone is E″, whose frequency is 5 times that of C.

In *open* pipes there is a node at the middle and a loop at each end. Consequently the whole series of overtones can be produced in open pipes. The first overtone of a C open pipe is C′; the second overtone is G′, and the third overtone is C″.

When a hole is bored in a pipe, it produces the same effect as if the pipe were cut off at that point. A loop or anti-node is produced at the opening. Wind instruments of nearly all kinds have several holes so that the length may be varied to produce notes of varying pitch. Such holes may be closed again by the finger or by means of a valve.

Fig. 400. — Saxophone.

353. Wind Instruments. In many wind instruments, a vibrating air-jet is the source of sound. The air-

jet may be produced by a vibrating reed as in the organ, harmonica, accordion, clarinet, or saxophone. Some organ pipes have a vibrating reed. A bellows is sometimes used to throw the reed into vibration. (See Figs. 399 and 400.)

In the flute, fife, and piccolo the vibrating air-jet is produced in the same manner as in the organ pipe. A stream

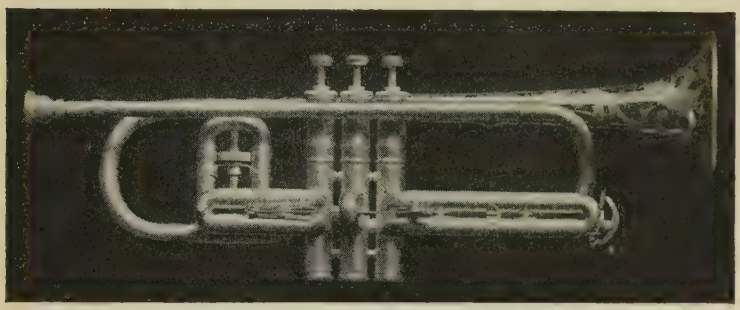


FIG. 401. — Cornet.

of air is directed against the edge of an opening near one end of the instrument. The pitch is regulated by the length.

In the cornet, trombone, and bugle the lips of the player

FIG. 402. — Slide trombone.

vibrate. The frequency depends upon the length of the tube. In the cornet, openings regulated by valves produce variations in pitch by changing the length of the pipe. (See Figs. 401 and 402.)

354. The Player Piano. In the operation of the player piano large bellows driven by the foot pedals are used to produce a partial vacuum in the wind chest *L*, Fig. 403. A

perforated music roll passes over the tracker bar N, which has 88 small openings, one for each key of the piano. From each opening in the tracker bar a tube M leads to the wind chest. When the holes in the music roll coincide with the openings in the tracker bar, a pulse of air is sucked into the corresponding tube. This air lifts a leather disc and the valve in one of the pneumatics, thus closing one port and opening the port directly beneath the valve. The air pressure collapses the movable leaf of the pneumatic H, which controls the hammers through a set of levers, Fig. 404. The surplus air in the tube is removed through an opening, which is called the "bleed."

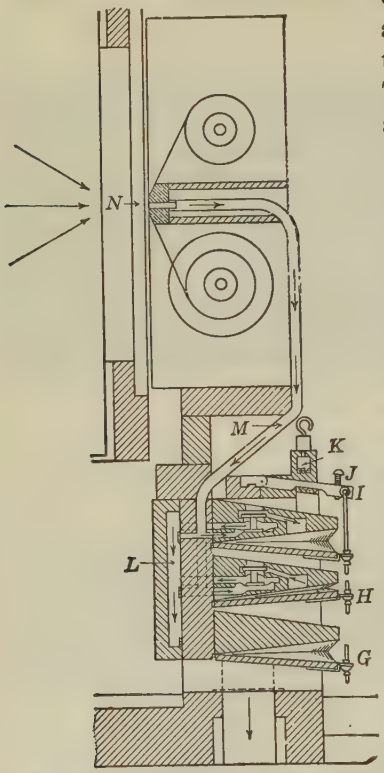


Fig. 403. — Player piano pneumatics.

355. Vibrations of Bells and Plates. When bells and plates vibrate, notes are produced which are not whole number multiples of the *fundamental*. Although they are not whole number multiples of the fundamental, yet they are called overtones. For this reason chimes are played by striking the bells in succession. Fig. 405 shows some complex figures produced by bowing a metal plate covered with fine sand. Nodes may be formed at various positions by touching the edge of the plate with the thumb and finger. In each case

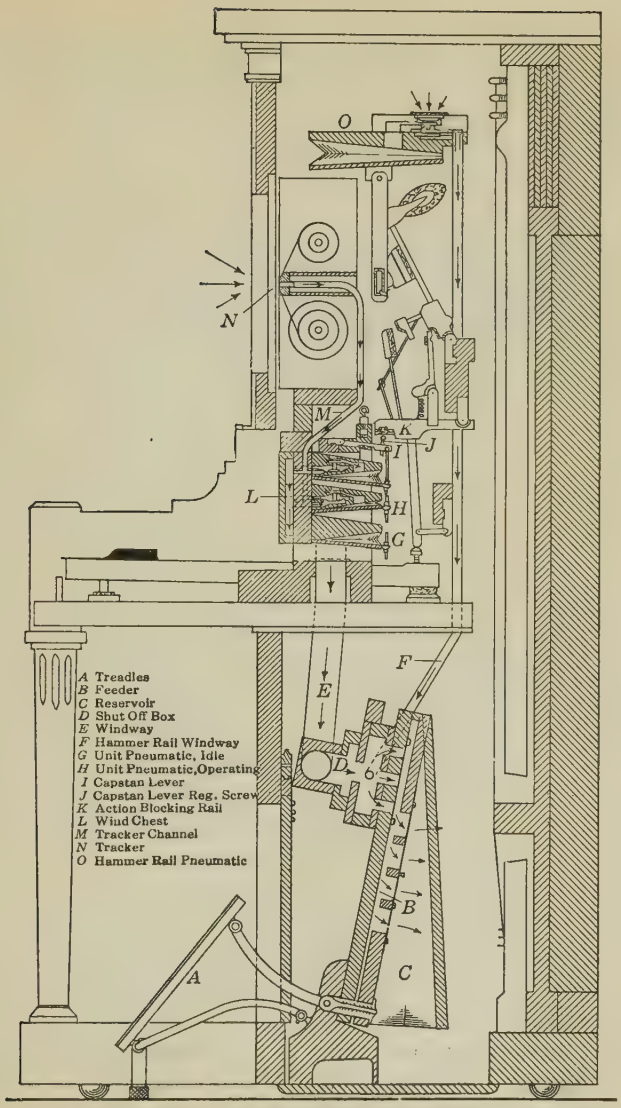


FIG. 404. — Player piano mechanism.

the plate is touched at A and C to produce nodes; it is bowed at B. The irregularity of the curves shows why it is quite impossible to have such plates produce harmony by simultaneous vibration. The patterns produced in this way are used as designs for wallpaper.

356. Vibrating Membranes. In some musical instruments, the vibrating part is a membrane. The tambourine, drum, and kettle drum are examples. The human voice is produced by the vibration of membranes. Two folds of ligamentous membrane which are stretched across the larynx, or Adam's apple, form the vocal cords. By the contraction of certain muscles these cords may be tightened at will. Variations of the tension produce notes of different pitch. In speaking, we learn to modulate the voice by varying the position of the tongue, palate, teeth, and lips. The quality of the voice depends upon the overtones which are made prominent by resonance. By cultivation a person may learn to suppress certain harsh overtones and reinforce others which are more pleasing.

FIG. 405. — Vibrating plates.

357. The Phonograph. This instrument is one of the inventions of Thomas A. Edison. For making the record, a mouthpiece having an elastic disc is used. This disc takes up the vibrations from the voice or some instrument, and, by means of a stylus attached to its center, cuts a groove in a wax cylinder, or traces a zigzag line over a greased metal disc. The metal disc is etched and an electrotype of copper is then made from it. From this electrotype several hundred copies of the original record are made by pressing it into hard rubber, condensite, or some composition material. The sound is reproduced by using a needle which follows the groove that has been made in the record. The needle is carried

by a diaphragm, which is thrown into vibrations of the same nature as those of the original sound. The diaphragm may be made of mica or duralumin. In the Edison reproducer it is made of several thicknesses of rice paper shellacked together. Vowel sounds are reproduced with somewhat greater exactness than the consonants, since they are more musical. The quality of the tone produced depends upon the needle used and upon the resonance of the amplifying horn of the instrument. Irregularities in the record itself may produce surface noises or scratching. With some records the groove is a lateral cut, and the reproducer is held in a vertical position, as shown in Fig. 406. In other cases, the cut is "hill and dale," so the diaphragm must vibrate up and down. The reproducer is held in the horizontal position shown in Fig. 407.

FIG. 406. — Phonograph reproducer (lateral).

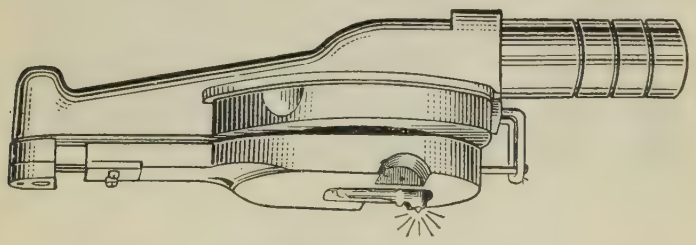


FIG. 407. — Phonograph reproducer (hill and dale).

A few years ago the engineers of the Bell Telephone Laboratories worked out a method of cutting phonograph records by means of an electrical mechanism. The sound waves are picked up by means of a special telephone trans-

mitter which translates them into fluctuating electrical currents that can be amplified by vacuum tubes in much the same manner that radio waves are amplified. These waves then operate an electro-magnetic recorder which cuts the record in a disc of soft wax. (See Fig. 408.) This new method of making records enables an operator to control

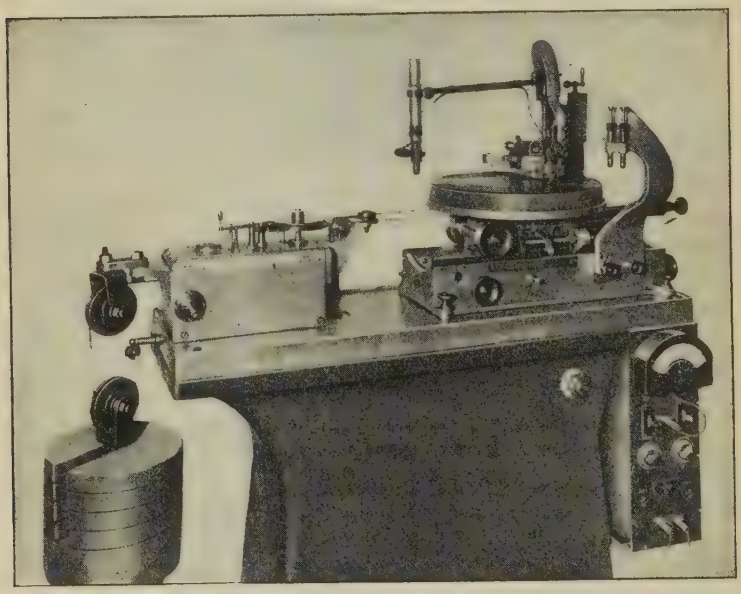


FIG. 408. — Mechanism used to cut phonographs electrically. *(Courtesy of Bell Telephone Laboratories.)*

the amplification, and it cuts into the records quite accurately those frequencies that begin about two octaves below middle C, and extend upward to include the entire upper range of the piano. The older records included only those frequencies lying between about 350 and 3000 vibrations per second. The "s" and "sh" sounds of speech were lacking and also the lower bass notes of music.

To reproduce the long waves of the bass notes of the *orthophonic* records, a much longer horn must be used. Horns 14 ft. or more in length have been built into orthophonic cabinets by folding the horn and tapering it properly. Ten bends are needed in placing a 6 ft. horn in a commercial cabinet. Fig. 409 shows a photomicrograph of a portion of an electrically-cut phonograph record. Such records may be electrically reproduced through a radio receiving set.

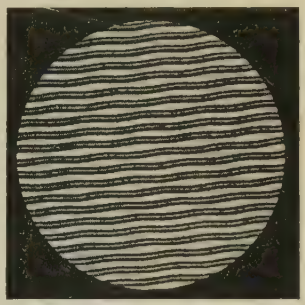


FIG. 409. — Photomicrograph of electrically cut record. (*Courtesy of Bell Telephone Laboratories.*)

358. Sound Waves Shown Graphically. A number of different methods of recording sound waves are now in use. In one of the simplest methods a stylus is fastened to a tuning fork, the stem of which is held firmly. A piece of smoked glass is then drawn beneath the fork so the point of the stylus traces its vibrations on the smoked glass. A smoked cylinder may be used in a similar manner.

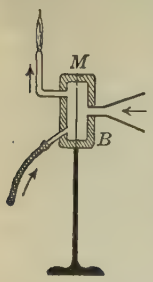


FIG. 410. — Manometric flame apparatus.

One early method used to picture sound waves was devised by Koenig. In the *manometric flame* apparatus, Fig. 410, M is an elastic membrane separating the two compartments of block B. There are two openings to the left-hand compartment, one fitted with a jet tube; the other is fitted with a tube connected to a gas-cock. The right-hand compartment has a single opening fitted with a funnel tube. The sound waves that enter this tube cause a corresponding vibration of the elastic membrane. As the condensations and rarefactions alternately compress the gas and then permit it to expand, the flame vibrates simul-

taneously. The vibrations of the flame are too rapid to be seen without the aid of a revolving mirror. When the membrane is not vibrating, a continuous band appears on the revolving mirror. An object sounding its fundamental produces a series of zigzag lines all of the same length. When overtones are produced with the fundamental, the lines are of varying length.

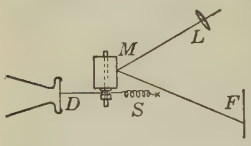


Fig. 411. — Phonodeik.

The *phonodeik* was invented by Dr. Dayton C. Miller of the Case School of Applied Science. By its use it is possible to photograph the wave forms of various instruments, or of the human voice. In Fig. 411, M is a tiny mirror which is free to oscillate on a small steel shaft mounted in jeweled bearings. A thin glass diaphragm D is set in the horn of a resonator. One end of a fine thread is attached to this diaphragm. The thread is then wrapped around a small pulley mounted on the mirror shaft, and the other end is fastened to a tension spring S.

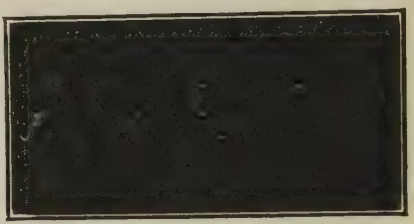


Fig. 412. — Vowel sound *oo* as in mood.

Fig. 413. — Vowel sound *ee* as in feed (note overtones).

A narrow pencil of light from the lens L is focused on the mirror, from which it is reflected to a sensitized film F, which moves at right angles to the mirror. As the sound waves enter the horn of the resonator, the diaphragm is thrown into vibration. These vibrations are transmitted through the thread to the mirror, causing it to oscillate on its axis. The pencil of light

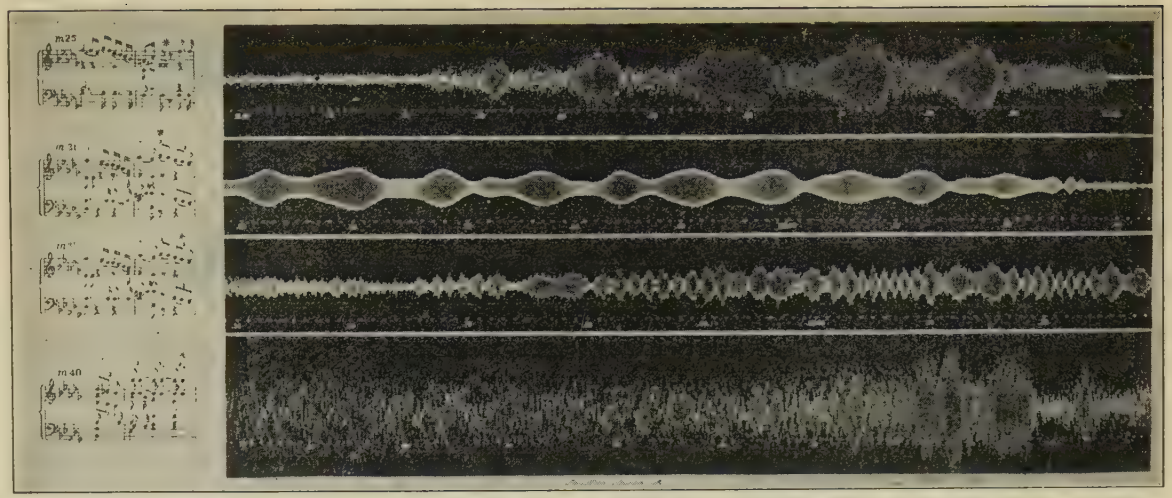


FIG. 414. — Sound vibrations photographed by Dr. Dayton C. Miller of the Case School of Applied Science. Music, Sextette from Lucia. Top line, as sung by Caruso. Second line, as sung by Tetrazzini. Third line, as sung by Amati and Tetrazzini. Bottom line, as sung by the sextette. The numbers show the time of exposure of film in tenths of seconds. Time for top score, one second. The modern phonograph makes it possible to engrave the vibrations of the human voice on permanent records made of wax, gutta-percha, or some other plastic, and then reproduce them at pleasure. Dr. Miller's phonodeik photographs the sound vibrations and enables us to study the fundamentals and overtones produced by the voices of renowned artists.

reflected from the mirror, traces on the film the sound waves that act upon the diaphragm. Figs. 412 and 413 show the fundamentals and overtones produced by vowel sounds. Some of the effects produced by singing voices are represented in Fig. 414.

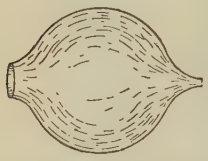


Fig. 415. — Helmholtz resonator.

359. Helmholtz Resonators. Complex sounds may be analyzed and studied by means of a set of resonators of the type devised by Helmholtz. (See Fig. 415.) The series of resonators consists of a set of hollow spheres, of such size that each one produces resonance with a note of a certain pitch. By placing the large opening near a body producing complex sounds and holding the small opening to the ear, it is possible to pick out all the overtones that are present, if a series of resonators is used one after another.

Complex sounds have been analyzed by this method and then reproduced by using electrically driven tuning forks to represent each of the various frequencies that were identified by the resonators. (See Fig. 416.) Some of the vowels have been reproduced in this way.

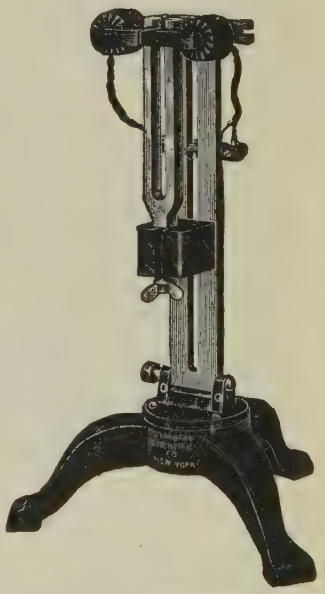


Fig. 416. — Electrically driven tuning fork.

SUMMARY

The major chord is built up of notes whose frequencies have the ratios 4, 5, 6, and 8. The major diatonic scale consists of eight notes in each octave for any given key.

The chromatic scale adds five notes per octave. In the equally tempered scale, the interval is uniform; the twelfth root of two is used.

Discord is a phenomenon of beats. About 30 beats per second produce the worst possible discord. If fewer than 5, or more than 60 beats reach the ear per second, the notes are not discordant.

A string vibrating as a whole produces its fundamental, or the note of lowest pitch it can give. A frequency which is a multiple of the fundamental is called an overtone.

The frequency of a vibrating string is inversely proportional to its length, its diameter, and the square root of its density; it is directly proportional to the square root of the tension.

In musical instruments the sound waves are generally caused by vibrating strings, or air-jets. Air-jets may be set up by reeds, by the vibrations of the lips of the player, or by striking the edge of an opening.

A closed organ pipe is one fourth as long as the sound wave it produces; an open pipe is one half as long as the sound wave it produces.

In an open pipe the whole series of overtones is possible; in a closed pipe only those overtones whose frequencies are *odd* multiples of the fundamental are possible.

The overtones of bells and plates are not whole number multiples of the fundamental. They do not produce harmony when struck simultaneously.

Complex sounds may be analyzed graphically by the manometric flame; the Helmholtz resonators are also used to pick out the overtones in complex sounds.

QUESTIONS

1. What is the first overtone of C? of G? of E′?

2. Why is there a discord when C and B are struck at the same time?

3. What is the vibration rate of the sixth overtone of C? To what letter on the scale does it correspond? Why is it desirable to supress the sixth overtone?

4. Why is a violin string bowed near one end instead of in the middle?

5. How is the pitch varied in ordinary whistling?

6. Do sound waves ever cast shadows?

7. Why does pressing the soft pedal of a piano decrease the loudness? Is the mechanism for softening the same with upright and grand pianos? Explain.

8. Does pressing either the loud or soft pedal of the piano affect the pitch of the notes? Explain.

9. Several notes may be blown on a bugle of unvarying length. Explain.

10. How does opening the holes of a saxophone or clarinet affect the pitch?

11. Why does increasing the speed of a phonograph raise the pitch?

12. Why does a short phonograph needle make the sound louder? (The student should observe that the phonograph needle is really a lever.)

13. How is the quality of the human voice modified? Where is the resonance produced?

14. A piano is properly tuned at 70° F. Is it in tune when the temperature rises to 80° F.? Explain.

15. What laws of strings are exemplified in the construction of a violin? Which law is illustrated in the tuning of stringed instruments? Which law does one use as he plays a stringed instrument?

16. When a large sea shell is held to the ear, a roaring noise is generally heard. Explain.

17. Why do windows sometimes rattle when the low notes of a pipe organ are sounded?

PROBLEMS

1. Compare the frequencies of two strings. A is one meter long and has a diameter of 0.5 mm. B is 50 cm. long and 1 mm. in diameter.

2. A string stretched by a force of 25 Kgm. gives the note E. What stretching force is needed to yield the note G?

3. A string 27 in. long produces the note C. Find the length of a similar string that will produce the note G.

4. Calculate the frequency and the wave length of the lowest

note on the piano, A_4, a little more than three octaves below middle C, when the temperature is 20° C.

5. Calculate the frequency and the wave length of the highest note of the piano, C′′ ′′, when the temperature is 20° C.

6. How long must a closed pipe be to give the note G, if the velocity of sound is 1130 ft. per second? To produce the note E′?

7. Calculate the vibration rate of the first overtone of an open pipe that gives the note C′. The third overtone.

8. What is the frequency of the first overtone of a closed C′ organ pipe? The second overtone?

9. A string 40 cm. long produces the note E, 320 vibrations per second. How much must the string be shortened to produce the note C′, 512 vibrations per second?

10. The frequency of a string 40 cm. long, 1 mm. in diameter, and stretched by a force of 36 Kgm. is 400. Calculate the frequency of a second string of the same material 100 cm. long, 0.75 mm. in diameter, and stretched by a force of 64 Kgm.

CHAPTER 16

LIGHT

A. NATURE AND VELOCITY

Vocabulary

Luminous, emitting light.
Illuminated, shining because of ability to reflect light received from outside sources.
Incandescent, glowing because it is heated to luminosity.
Photometer (*phos*, light; *meter*, measure), an instrument used to measure candle power.

360. Nature of Light. It is a fact capable of demonstration that sound is transmitted to the ear by means of waves traversing some medium. In the study of heat we learned that heat energy may be transmitted by waves in the ether. At the present time, it is generally believed that ether waves may produce various other effects. Some of them affect a photographic plate and cause it to darken rapidly. Others affect our radio sets and make wireless transmission possible. Those ether waves that affect the optic nerve are called *light waves*. The effect that ether waves produce seems to depend upon their length. The optic nerve is sensitive to waves which have certain lengths, just as our ears are affected by air waves of certain lengths. Heat waves and wireless waves are longer than light waves. Some waves that affect a photographic plate and do chemical work are much shorter.

361. Theories of Light. Although Huygens proposed his wave theory of light as early as 1678, it was not generally accepted before the beginning of the nineteenth century. Prior to that time the corpuscular theory met with greater favor, largely through the influence of Sir Isaac Newton.

According to the *corpuscular* or *emission theory*, streams of extremely small particles are emitted by *luminous* bodies. Such corpuscles produce the sensation of light when they enter the eye and stimulate the optic nerve. Newton's influence upon scientific thought was great enough to delay the acceptance of the wave theory for about 100 years.

When Huygens *assumed* the existence of the *ether* as a medium through which light waves are transmitted, men of the eighteenth century found it difficult to accept his theory. It is difficult today to try to picture a medium which we cannot see, feel, smell, or taste. We accept this idea of a weightless fluid pervading all inter-molecular space because some of the phenomena of light cannot be explained by any other method that is wholly satisfactory.

As early as 1864, James Clerk-Maxwell, one of the greatest of modern physicists, suggested that light has its origin in ether waves set up by means of electrical disturbances. A few years later the experiments of Heinrich Hertz confirmed Maxwell's suggestion. At the present time the *electromagnetic theory of light* is commonly accepted. Light waves are believed to be ether waves which have their origin in the vibrations of electrically charged particles that compose the atom.

362. Light Waves Differ from Sound Waves. In several ways sound waves differ from light waves: (1) Light waves travel through a vacuum, while sound waves do not. Hence light waves are ether waves, but sound waves must be transmitted by ordinary matter; (2) light waves are transverse, while sound waves are longitudinal; (3) sound waves vary in length from about 1 cm. to nearly 21 meters, while light waves range from 0.000039 cm. to only 0.000081 cm. in length; (4) light waves travel in straight lines, but sound waves bend around corners readily. We can hear a person who stands around the corner from us, but we cannot see him; (5) light travels so rapidly that it is con-

sidered instantaneous for short distances. The speed of sound is very slow compared to that of light. In one second light travels a distance equal to more than seven times around the earth at the equator.

363. Sources of Light. Nearly all the *natural* light we receive comes from the sun. The distant stars also supply us with some light. Some of the stars are much larger than the sun and produce far more light, but they are so far away that we receive only a small fraction of the light which they emit.

Dr. Michelson of the University of Chicago devised a method of measuring the diameter of some of the stars. He found that Betelgeuze, a star in the constellation Orion, has a diameter much greater than that of our sun. If this star were placed at the center of our solar system in place of the sun, its edge would extend out beyond the orbit of the earth to the orbit of the planet Mars, about 150,000,000 miles from the center of our solar system. This star has a diameter of about 300,000,000 miles, while the diameter of the sun is only 866,000 miles.

Artificial light may be produced by friction or by chemical action. When gas, oil, or other fuel burns, light is produced. Light is produced artificially when an object is heated until it glows, or is heated to *incandescence*. The incandescent lamp and the Welsbach mantle used in gas lights are examples.

364. Luminous and Illuminated Objects. When a platinum wire is heated, the ether waves that are set up become shorter and shorter as the temperature rises. The wire soon begins to glow, or it becomes incandescent. It is a *luminous* body, visible on account of its own light. An object that gives off light on account of the energy of its own oscillatory particles is said to be luminous. The stars are luminous and emit light.

Just as sound and heat are reflected, so light waves may be turned back from the surfaces of bodies. Mirrors reflect

light that is received from some other source. A body that merely reflects light which it has received is an *illuminated body*. The moon is an excellent example. Like a huge mirror, it reflects light which it receives from the sun. Some of the planets may be hot enough to be luminous, but most of them are illuminated bodies, reflecting light received from other sources.

365. Reflection, Absorption, and Transmission of Light. When light waves are incident upon the glass of our windows, some of the light is reflected by the glass, a part is absorbed by it, and part is transmitted. When light waves strike other bodies, they are affected in three different ways:

(1) *Reflection.* Smooth water has been used as a reflector of light from the earliest times. Glass reflects light, but more of the light is reflected if one side of the glass is silvered. Highly polished metals make good reflectors. It is estimated that the planet Venus reflects about 50% of the light it receives.

(2) *Absorption.* Dark-colored objects are good absorbers of light waves. Black objects absorb all the light they receive. When the *vertical* rays of the sun fall upon a body of water, they are largely absorbed or transmitted; when the sun's rays strike the water at a very oblique angle, more of the rays are reflected. So much light is reflected by the water that we are dazzled by the reflected rays from the setting sun.

(3) *Transmission.* Air, glass, and water transmit light readily. They are said to be *transparent.* So much of the light is transmitted by transparent bodies that objects can be distinguished through them. Formerly oiled paper was used in windows as a substitute for glass. Light passes through the paper, but *one cannot distinguish objects* through it. Frosted bulbs and some lamp shades are also examples of *translucent* substances. They transmit some light, but it is diffused so much that objects cannot be identified.

Opaque objects do not transmit light. Hence we cannot see through them at all. Since the clearest water, or air itself, absorbs some light, no substance is perfectly transparent. On the other hand, no object is perfectly opaque. Gold transmits some light when it is beaten into extremely thin sheets. Steel may be ground into sheets so thin that strong light is transmitted. With our eyelids closed, we can tell when a light has been turned on in a darkened room.

366. Rays, Beams, and Pencils of Light. From a luminous point, light waves travel outward in all directions. If the medium is of the same nature throughout, the light travels in straight lines. When one aims a rifle he makes use of this fact, since the light from the object at which he aims is reflected along the two sights of the rifle. A single line of light coming from a luminous point is called a *ray*. Several parallel rays form a *beam* of light. The rays coming from the sun are so nearly parallel that we may consider them as beams. When several rays of light come from a point they form what is called a *diverging pencil*. Rays from an automobile headlight are somewhat diverging. Several rays of light proceeding toward a point form a *converging pencil*. When the sun's rays pass through a burning glass, they are bent as they pass through the glass. They converge to a point called a *focus*.

367. Shadows and Eclipses. Since an opaque object absorbs light, the space behind it is in darkness. Any space from which the light is excluded by an opaque object is called a *shadow*. When the source of light is a point, as in Fig. 417, all the rays will be cut off from the dark part of the screen *S* by an opaque ball *B*. If the light comes from a spherical object, the shadow will vary in intensity. (See Fig. 418.) The part from which all the rays of light are excluded, included in the cone *DCF*, is called the *umbra*. The lighter

FIG. 417.—Umbra, or dark shadow.

parts of the shadow, CFy and CDx, are called the *penumbra.* The luminous ball S is not entirely hidden from an observer between x and C, but part of its rays are cut off.

We may also use Fig. 418 to show how *eclipses* are formed. Suppose we let S represent the sun, E the earth, and M the moon. As the moon revolves around the earth, it may pass through the earth's shadow. At the position M we see the moon passing from the earth's penumbra into its umbra. Since the moon does not shine by its own light, it is dark when the sun's rays are cut off by the earth.

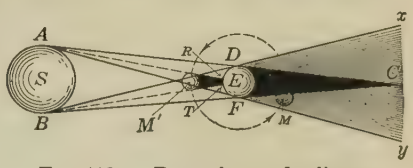


FIG. 418. — Penumbra and eclipses.

During an eclipse of the sun, the sun's rays are intercepted by the moon so that they do not reach the earth's surface. When the moon is in the position shown at M', the sun will be totally eclipsed for an observer at any place on the earth between R and T.

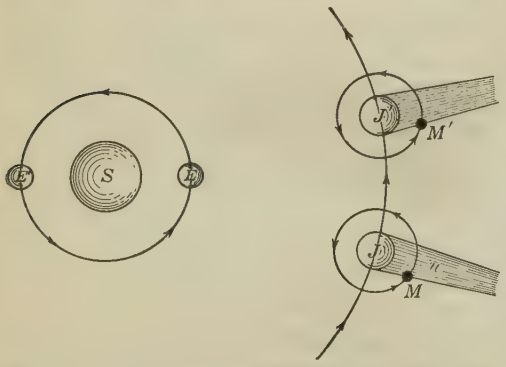


FIG. 419. — To show how velocity of light was determined.

368. Velocity of Light. Light travels so fast that it appears to be instantaneous. In fact, Galileo concluded that no time at all was required for light to travel from one place to another. His conclusion was accepted until the year 1675, when Roemer, a Danish astronomer, found a method for measuring the velocity of light. He watched the time of the eclipses of

one of Jupiter's satellites or moons, first when the earth was on the side of the sun nearest to Jupiter and six months later when the earth was on the opposite side of the sun. From Fig. 419, we see that the satellite M is just entering the umbra of the planet Jupiter. Roemer observed this eclipse from the earth at the position E. Six months later the earth was at E', on the opposite side of the sun from Jupiter, which in the meantime had moved to the position J'. From E' Roemer observed the eclipse of the same satellite M'. But in this particular case, he found that the eclipse occurred 16 min. and 36 sec. later than the time that it should have occurred from his calculations. He knew that he was 186,000,000 miles farther from Jupiter than before. Hence he concluded that the difference in time must be the time actually required for light to travel across the earth's orbit. If light travels 186,000,000 miles in 996 sec., then the velocity of light must be a little more than 186,000 miles per second.

Other methods for finding the velocity of light were used by Foucault in France, and Michelson of the University of Chicago. These observers found that light has a velocity of a little more than 186,000 miles per second. They also determined the velocity of light in some solids and liquids. The velocity in water is about three fourths as great as in air; in ordinary glass it is about two thirds the speed in air. Light travels slightly faster in a vacuum than it does in air.

B. PHOTOMETRY

369. Illumination. In the study of sound we learned that an intense sound would not seem very loud to an auditor at a considerable distance from the source. Similarly, an intense light may appear quite dim to an observer stationed a long distance from the light source. The amount of light one receives must depend upon two factors: the *intensity* of the light itself, and the *distance* we are from it. If we

consider Fig. 420 we can understand why a light appears to grow dimmer as we move farther away. The light is emitted from a luminous point at P, and it spreads out in all directions. Suppose we place the screen A, which has an area of just 1 sq. ft., exactly 1 ft. from the light source. B, which is four times as large, is placed 2 ft. distant; and C, which has nine times the area of screen A, is placed 3 ft. away. Both the screens B and C are completely shaded by the screen A. When the screen A is removed, then those rays of light which had illumined A will fall upon the screen B. But B has an area of 4 sq. ft., while the area of A is only 1 sq. ft. Hence each sq. ft. of surface at B, 2 ft. from the light source, can receive only one fourth as much light as 1 sq. ft. of surface at A, only 1 ft. distant. Likewise, C is three times as far away as A, and the light will be spread over nine times as much area. Thus 1 sq. ft. of surface will receive only one ninth as much light at C as at A.

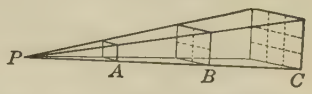


FIG. 420. — Effect of distance on amount of illumination.

These observations, which can be verified by experiment, may be summarized in a general statement known as the LAW OF ILLUMINATION. *The amount of light a body receives is inversely proportional to the square of its distance from the source of light.* A man who is 20 ft. from an arc light will receive only one fourth as much light as one who is only 10 ft. away. Illumination is measured in *foot-candles.*

It is obvious that we would need a light nine times as intense to illuminate as strongly a screen 3 ft. away as a similar screen only 1 ft. distant. A reading lamp 1 ft. away from our book supplies us with as much light as a ceiling lamp 36 times as intense, if the ceiling lamp is 6 ft. from our book. Intensity is measured in *candle power.* The LAW OF INTENSITY follows: *The intensities of lights, or their candle powers, must be directly proportional to the squares of*

their distances from a screen which they illuminate with the same intensity. The student must not confuse this *law of intensity* with the *law of illumination.* The former depends upon the energy produced by the luminous body, and the latter upon the amount of that energy which an illuminated body receives. (See Fig. 421.)

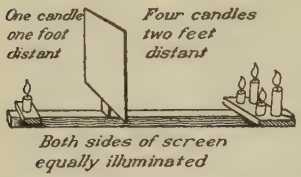


FIG. 421. — Illumination is inversely proportional to the square of the distance.

370. How Light Is Measured. In all systems of measurement, some standards must be used. From the preceding section, it seems reasonable to expect that at least two standards must be used for measuring light; one to determine the intensity of the light source and the other to measure the amount of light an illuminated body receives.

The *standard candle* is used to measure the intensity of light. A light of 10 candle power gives out 10 times as much

ANGLE	CANDLE-POWER
0	1420
5	1480
15	1610
25	1780
35	1830
45	1810
55	1650
65	1080
75	441
85	51
90	

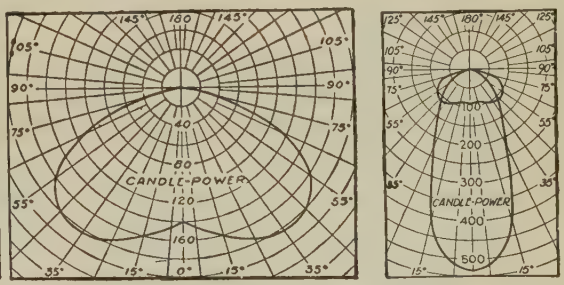


FIG. 422. — The cut at the left shows how light is distributed. Horizontal candle power is shown at 90° and vertical at 0°. The cut at right shows the effect of the reflector.

light as a standard candle. The standard formerly used was a sperm candle burning 120 grains of wax per hour. Such a candle has to be kept carefully trimmed to give exactly one candle power of light. At the present time incandescent electric lights are nearly always used instead of the standard

candle, since the amount of light they emit is very constant if the voltage does not vary.

Incandescent lamps used for interior lighting generally range from 12 candle power to 100, although high candle power, argon-filled bulbs are sometimes used. The ordinary arc light gives about 500 candle power; the flaming arc may give from 800 to 1200 candle power. Searchlights frequently give several million candle power.

If we observe closely the ordinary tungsten lamp suspended vertically with the shade removed, we notice that the light emitted horizontally is much more intense than that given off vertically. Candle power may refer to horizontal illumination, or to illumination in any direction. The candle power of the arc light as already given is the average of the candle powers in all directions, or its *mean spherical* candle power. The maximum candle power of the arc light is much more than 500. (See Fig. 422.)

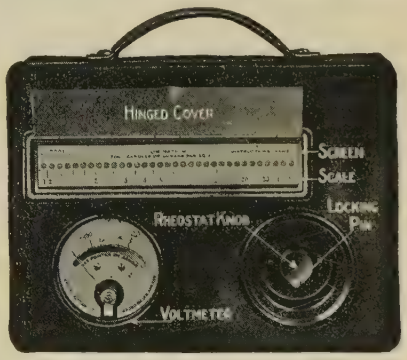


FIG. 423. — A miniature lamp inside the foot-candle meter illuminates the translucent spots on the screen. The instrument is read by finding that particular spot where the illumination from within equals that on the outside which is to be measured.

The *foot-candle is used to measure illumination.* As the name implies, the foot-candle must depend upon the candle power of the light and the distance. *The foot-candle is the amount of light one would receive from a standard candle at a distance of one foot.* A person seated 1 ft. from a 20 C.P. lamp receives 20 foot-candles of light. (See Fig. 423.) If he sits at a distance of 2 ft. from such a lamp, he receives only five foot-candles.

$$20 \div (2)^2 = 5. \quad \text{(LAW OF ILLUMINATION.)}$$

The number of foot-candles may be found by dividing the candle power of the light by the square of the distance measured in feet.

$$\text{Foot-candles} = \frac{\text{C.P.}}{d^2}$$

In illuminating engineering, the *lumen* is an important unit that is much used. It denotes the quantity or amount of light. If we place a standard candle at the center of a sphere of one foot radius, the amount of light falling upon one square foot of the inner surface of the sphere is one lumen. Or, if we cut in the sphere an opening whose area is exactly one square foot, the amount of light escaping from the opening is one lumen. If we make the size of the opening two square feet, then two lumens of light escape. Since the area of such a sphere is 12.57 sq. ft., then the total amount of light emitted by a candle is 12.57 lumens. Of course if we have a 2-C.P. light at the center of a sphere of one foot radius, the amount of light falling upon every square foot of area is two lumens. Hence,

lumens = foot-candles × area in square feet.

371. Amount of Light Needed. The number of foot-candles needed varies with the kind of work one is doing. Too much light is quite as injurious to the eyes as too small an amount. For reading ordinary print, for writing, or for work on light-colored materials, about 6 foot-candles of light are sufficient. For reading a closely printed page of smaller type, 10 foot-candles of light may be needed. One who uses fine thread for sewing, especially with black goods, requires at least 15 foot-candles.

Formerly many factories were poorly lighted. Now engineers make a study of the lighting problems, because sufficient light speeds up the work and causes fewer accidents.

Efforts are made to eliminate glare and also to prevent shadows.

Since the number of foot-candles we receive depends upon both the candle power of the light and the distance, one may economize by placing his lights as near as possible to the objects to be illuminated. A 25-watt lamp furnishes about 20 C.P., and a 50-watt lamp yields about 40 C.P. One seated 2 ft. from the former receives more light (5 foot-candles) than he would if seated 3 ft. from the latter (4.4 foot-candles), but he pays twice as much for the latter as he would for the former.

372. How Candle Power Is Measured. In order to find the candle power of a light, we must compare the amount of light it gives off with the amount emitted by a standard candle or lamp. Several types of *photometers* have been devised to measure candle power, nearly all based upon some method of illuminating one side of a screen or object exactly the same by the light of unknown candle power as the *opposite side is illuminated* by the standard candle.

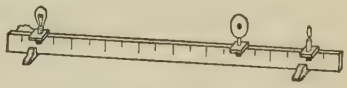


FIG. 424. — Bunsen photometer.

In the Bunsen photometer, Fig. 424, a piece of paper, in the center of which there is a grease spot, is placed on a meter stick between the standard candle and the lamp of unknown candle power. This paper is moved from side to side until it is equally illuminated on both sides. If we hold such a sheet of paper toward the light, the spot appears lighter than the surrounding paper. If we turn the paper from the window and examine it by reflected light, the spot appears darker, since the grease spot is a poor reflector of light. When the paper is equally lighted on both sides, the spot practically disappears. Then the distances from the grease spot paper to the standard and to the lamp of unknown candle power are both carefully measured. *The candle powers of the two light sources are directly propor-*

tional to the squares of their distances from the screen. (LAW OF INTENSITY.)

Suppose we use a 20 C.P. lamp as our standard. The screen is equally illuminated when it is 20 cm. from the standard and 80 cm. from the lamp of unknown candle power. Evidently the unknown lamp must have the greater intensity, since it supplies as much light at a distance of 80 cm. as the standard does at a distance of 20 cm. It must be $\frac{(80)^2}{(20)^2}$ times as intense. Hence, its candle power equals $\frac{(80)^2}{(20)^2} \times 20$, or 320 C.P.

The Joly photometer is a convenient type for student use. Two blocks of paraffin separated by tin foil are used instead of the greased paper. The light on either side is transmitted by the paraffin, but not by the tin foil. By comparing the depth of illumination at the edges of the two blocks it is easy to determine when the illumination on both sides is equal. The method of finding the candle power is the same as with the Bunsen type photometer.

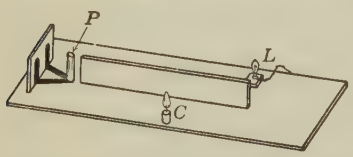


FIG. 425. — Count Rumford Photometer.

In the Count Rumford photometer, Fig. 425, the standard candle and the lamp of unknown candle power are separated by a wooden screen. They are then adjusted at such distances that the shadows cast by the wooden post P are of equal intensity. The candle power is then determined by finding the ratio of the squares of their distances from the post.

SUMMARY

Like heat, light is also a form of radiant energy. It travels in straight lines at a velocity of about 186,000 miles per second.

An object may reflect, absorb, or transmit the light waves it receives.

That part of a shadow formed by the exclusion of all the light is called the umbra; the part from which only a part of the light is excluded is called the penumbra.

The amount of light a body receives is directly proportional to the intensity of the luminous object and inversely proportional to the square of the distance between the source of light and the illuminated body.

Photometry deals with the measurement of the intensity of light. Intensity is rated in candle power; the amount of illumination received is rated in foot-candles.

QUESTIONS

1. Could there be an eclipse of the moon at new moon? Give a reason for your answer.

2. Do light and heat travel at the same velocity? Give a reason for your answer.

3. In describing eclipses, an almanac speaks of the moon as entering the earth's penumbra and its umbra. What do these expressions mean?

4. Upon what two factors does the amount of light one receives depend? How is each one varied?

5. If an object were perfectly transparent, would it be visible? Explain.

6. The moon is 240,000 miles from the earth. Show by a diagram why the sun can never be in total eclipse except for a small portion of the earth at a given time.

PROBLEMS

1. A is seated 2 ft. from a lamp of 30 C.P.; B is 3 ft. from the same lamp. How many foot-candles of light does each receive?

2. A stick 4 ft. long casts a shadow 5 ft. long; how high is a flagstaff which casts a shadow 100 ft. long?

3. The screen of a photometer is found to be equally illuminated when a 20 C.P. lamp is 10 cm. away and an arc lamp is 60 cm. distant. What is the candle power of the arc lamp?

4. A reads from a 20 C.P. lamp 2 ft. distant; B reads from a

100 C.P. lamp 5 ft. away. How many foot-candles does each receive? Compare the cost of operating these lamps.

5. A tree 60 ft. high is 180 ft. distant. How far from the eye must a pencil 6 in. long be held to appear the same height as the tree?

6. At one end of a meter stick a standard candle is placed. At the other end of the stick there is a lamp of unknown candle power. A screen which is equally illuminated on both sides is 15 cm. from the standard candle. Find the candle power of the lamp.

7. A reading room has a 12-ft. ceiling. Which is better, to light the room with 4 arc lamps of 500 C.P. each, suspended 2 ft. from the ceiling, or to use 16 incandescent lamps of 100 C.P. each, suspended 5.5 ft. from the ceiling? (Assume that the reading tables are 30 inches high.) Calculate the maximum number of foot-candles a reader would receive in each case.

8. For a certain piece of work a man needs 6 foot-candles of light. He has a 40 candle power lamp. How far away must the lamp be placed to give him the required amount of light?

9. What candle power lamp will yield 5 foot-candles of light at a distance of 3 feet?

10. The North Star is so far from the earth that it takes about 55 years for its light to reach us. How far away is it in miles? Give a good reason why astronomers express the distance of stars in light-years. (A light-year is the distance light travels in one year.)

11. At one end of a meter stick is a 32 C.P. lamp; at the other end there is a 9 C.P. lamp. Where must a screen be placed between the two to be equally illuminated on both sides? (*Hint.* Let x equal one distance, and $100-x$ the other.)

12. The planet Mars is about 140,000,000 miles from the sun. The earth is about 92,000,000 miles. Compare the relative amounts of heat and light each planet receives from the sun.

13. The radius of the sun is 433,000 mi.; the radius of the earth is 4000 mi.; the distance between the sun and the earth is 92,500,000 miles. In Fig. 418, AS represents the radius of the sun, ED the radius of the earth, and SE the distance between the sun and the earth. Calculate EC, the length of the earth's shadow. (*Hint.* Note that ASC and DEC are similar triangles. SC is equal to 92,500,000 miles plus x miles.)

CHAPTER 17

LIGHT—REFLECTION

Vocabulary

Aberration, wandering, or non-fucusing.
Aperture, an opening.
Diffusion, as applied to light; a scattering of light rays.
Virtual, apparent, or formed by imaginary rays.
Image, a picture or optical counterpart of an object.

373. Reflection of Light. The amount of light an object reflects depends upon the *nature of the material,* the *polish of the surface,* and the *angle at which the light strikes the surface.* Mirrors are highly polished to make them better reflectors. The glare of the rising or setting sun upon the water teaches us that more light is reflected when the rays are incident upon the surface at an oblique angle. At noonday it is not difficult to look at the image of the sun in the water, because perpendicular rays are more completely absorbed.

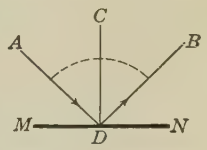


Fig. 426.— Law of reflection.

374. Law of Reflection. The reflection of light is not unlike that of sound, or the rebound of a ball. Suppose we let *MN* of Fig. 426 represent a reflecting surface. *AD* is a ray of light *incident* upon the reflector at *D;* and *DB* is the path of the reflected ray. *CD* is a perpendicular to the reflecting surface; in physics it is generally called the *normal.* The angle *ADC* is called the *angle of incidence;* the angle *BDC* is the *angle of reflection.*

By actual experiment it may be shown that *the angle of reflection is equal to the angle of incidence.* This statement, which is true of all cases, is known as the LAW OF THE REFLECTION OF LIGHT. If we increase the angle of incidence,

the angle of reflection is correspondingly increased. A ray of light incident upon a mirror along the normal is reflected back upon itself. The incident ray, the normal, and the reflected ray always lie in the same plane.

375. Regular Reflection. Every schoolboy has used a piece of mirror to reflect the sunlight into the eyes of some one across the room. Regular reflection from such surfaces produces so much glare that it is difficult to see clearly. The rays from the sun are nearly parallel, and have the same angle of incidence; hence they are nearly parallel as they are reflected from the mirror. Fig. 427 shows us how a beam of light is reflected from a polished, plane surface. One finds it hard to read from a glazed paper in strong sunlight. The fact that one may walk into large mirrors or plate glass is evidence that neither perfect reflectors nor transparent objects are easily visible.

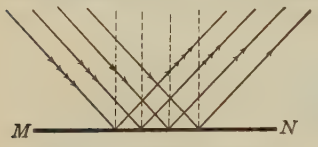


Fig. 427. — Regular reflection.

376. Diffused Reflection. If we refer to Fig. 428 it will be easy to understand what happens when a beam of light is incident upon an *irregular* surface. Of course the law of reflection holds true for each particular ray of light, but the normals to the surface are not parallel, and the light is scattered in all directions. The importance of such *diffusion*, or scattering of light can hardly be over-estimated. If the sun's rays were not diffused by rough surfaces and by dust particles in the air, the corners of a room and the space under shade trees would be in almost total darkness. In front of the windows the glare would be dazzling.

Fig. 428. — Irregular or diffused reflection.

377. How Diffusion Is Promoted. Our newspapers are printed on unglazed paper. They are easier to read because

the rough surface diffuses the light. Books are often printed on *semi*-gloss paper. Then they are not difficult to read, and the illustrations show more clearly than those from unglazed paper. Wall-papers are never glazed. Their roughened surfaces promote diffusion. The furniture and woodwork in our homes are often left with a dull finish to prevent regular reflection. Such surfaces soil more easily, however.

In many ways light is also *diffused by transmission.* Frosted electric bulbs, opalescent lamp shades and globes, prism glass for windows, and anti-glare lenses for automobile headlights are all examples.

378. Mirrors. A mirror is a highly polished surface that is used to form images by the regular reflection of light. For ordinary looking glasses *plane* pieces of ordinary or plate glass are silvered so that a large quantity of light may be reflected. For special purposes *curved* mirrors are used. Such curved surfaces may form part of a sphere, a cone, or a cylinder. Curved mirrors may be either *concave* or *convex.* When the outside surface of a sphere is the reflecting surface, the mirror is convex; the inside surface of a hollow sphere forms a concave mirror.

379. Image Formation. Rays of light are often reflected from a curved mirror in such a manner that they meet in front of the mirror to form an *image* of the object from which the light comes. Such a picture or visual counterpart of the object may be thrown upon a screen. An image of this kind, which is formed by the actual rays of light themselves, is called a *real* image. *Real images are always inverted.*

When a person looks at his own image in a plane mirror, the rays of light *appear to come* from behind the mirror. Of course the real rays of light are reflected from the surface of the mirror, but they *seem to meet* behind the mirror to form the image. An image of this kind is called a *virtual image.* Of course such an image cannot be thrown upon a screen.

Virtual images are always erect. In a subsequent chapter we shall learn that lenses are also used to produce images; it is also possible to produce images by letting light pass through very small openings.

380. Images Formed by Small Openings. If we punch a pin-hole in a window shade of a darkened room on the sunny side of the house, an image of the sun may be thrown upon a piece of white paper held a foot or more from the opening. An excellent image of a candle flame may be formed upon a white screen by letting the rays from the candle pass through a small aperture, as shown in Fig. 429. Since light travels in straight lines, a ray of light from A will pass through the opening and fall upon the screen at A'. From D a ray of light will be incident upon the screen at D'. If the opening is very small, the image will be well-defined, but not very bright. Increasing the size of the opening makes the image brighter, but it will be less distinct. A partial eclipse of the sun may be observed in this manner by throwing the sun's image on a screen in a darkened room. The pin-hole camera is also an application of this method of forming images. Fairly good pictures may be taken with such a camera.

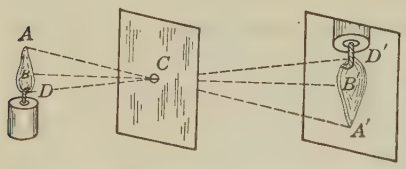


FIG. 429. — Images formed by small openings.

In Fig. 429, we note that the triangles ABC and $A'B'C$ are similar. Therefore, $AB : A\,B' = BC : B'C$. But, AB is equal to one half the size of the object, and $A'B'$ is equal to one half the size of the image; BC equals the distance of the object from the aperture, and $B'C$ is equal to the distance of the image from the aperture. Thus we prove that the relative sizes of the object and the image are proportional to their relative distances from the opening. Increasing the distance of the object decreases the size of the image. By

moving the screen farther from the opening, the size of the image is increased.

PROBLEM. An object 6 ft. tall is 8 ft. from an aperture which forms an image on a screen placed 4 in. from the opening. Find the size of the image.

Solution. Size of object : size of image = object distance : image distance. Substituting, 72 in. : x in. = 96 in. : 4 in. Whence, x equals 3 in., the size of the image.

381. Images Formed by Plane Mirrors. When one looks at his image in a plane mirror, he finds that his image is neither enlarged nor reduced; it is erect; it is virtual, since the rays seem to come from behind the mirror; it is as far behind the mirror as the observer is in front. Since the image is formed on the *normal* produced, it will be reversed; the right side will appear as the left side of the image, and vice versa.

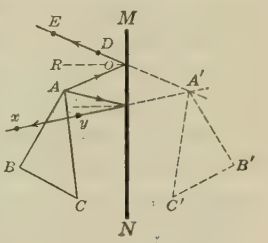


FIG. 430.— Images in plane mirrors.

By laboratory experiment it is possible to construct the image of an object as formed by a plane mirror. Let us use for the object a triangle, ABC, drawn upon a sheet of paper. (See Fig. 430.) The mirror is placed on the line MN. A pin is then placed at the vertex A of the triangle. By looking at the image of this pin in the mirror, it will be found possible to arrange two pins, E and D, in line with the image of the pin at A as seen in the mirror. Since light travels in straight lines, the image of the pin will be on the line ED produced behind the mirror. In the same manner we may set two pins, x and y, in line with the image of the pin at A. The image is also on this line produced. Since A', the point of intersection of the two sight lines, is the only point common to both lines, the image of A must be at the point A'. By the same method, it is possible to locate the

image of the point B at B', and of the point C at C'. In all these cases *the image is found to be as far behind the mirror as the object is in front.* By joining the points, we prove that *the image is the same size as the object.*

This method of constructing images also verifies the law of reflection of light. As we look along ED, we see the ray of light coming from A. It is incident upon the mirror along the line AO; from the point O it is reflected along ED. When we erect a perpendicular or normal to the mirror at O, we bisect the angle AOE. The angle EOR, which is the angle of reflection, is equal to the angle of incidence AOR.

382. Uses of Plane Mirrors. By Ovid we are told that Narcissus became so infatuated with his image in the water that he was changed into the flower which bears that name. From the very earliest times mirrors have been used as looking glasses. We also use them in our houses for their decorative effect. They are frequently used by the army signal corps for flashing signals. It is also possible to use plane mirrors for producing optical illusions on the stage, since the image is a virtual one. In the production of the stage ghost the audience looks through a large piece of plate glass and sees upon the stage the virtual image of an actor who is behind the scenes. Nearly all closed automobiles are fitted with plane mirrors to enable the driver to see cars behind him.

383. Multiple Reflection. Just as sound waves bound and rebound between parallel cliffs or walls to produce echoes and re-echoes, so light waves are reflected back and forth between parallel mirrors or mirrors set at an acute angle, forming multiple images. The image formed in one mirror acts as the object which forms an image in the second mirror. Another image of this image may then be formed. Since some light is absorbed each time, each succeeding image is fainter than the one just preceding. The kaleidoscope is an example of multiple reflection. Three mirrors set at

angles of 60° form multiple images of vari-colored pieces of glass.

A thick plate-glass mirror also shows multiple reflection because both surfaces are reflectors. Fig. 431 shows how the ray of light AB is partially reflected to C; a part passes through the glass to D, the back of the mirror, whence it is again reflected. The path the ray may take is shown by the arrowheads. When it reaches the front surface, it is divided; a part enters the air, and a part is reflected to the back surface again. A gas-jet or electric light as viewed in a plate-glass mirror shows such a series of images.

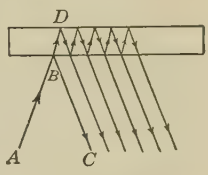


FIG. 431. — Multiple images.

384. Terms Used with Curved Mirrors. Before one can understand how images are formed by curved mirrors, it will be necessary to define several terms which are used. Let us assume that the mirror we are using is part of the surface of a sphere. We represent the mirror by the arc of a circle. By the use of Fig. 432 these definitions may be clarified.

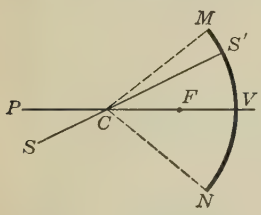


FIG. 432. — Definitions pertaining to curved mirrors.

(1) The *center of curvature* C is the center of the sphere of which the mirror forms a part. (2) The *aperture* is the angular portion MCN of the sphere that is included by the mirror. Generally only a few degrees of the total surface are used as the reflecting surface. (3) The *vertex* V is the center of the mirror itself. (4) The *principal axis* is the line PV drawn through the center of curvature and the vertex. (5) Any other line drawn through the center of curvature, SS' for example, is called a *secondary axis*. (6) The *normal* to the surface of a concave mirror is the radius drawn from the point of incidence, since the radius is per-

pendicular to a tangent to the surface. In a convex mirror, the normal is the radius produced.

385. How Light Waves Are Focused. Let us draw two lines AD and BE to represent rays of light parallel to the principal axis, both incident upon a concave mirror as shown in Fig. 433. From the points of incidence we draw the normals CD and CE. By construction we make the angles of reflection CDF and CEF exactly equal to the angles of incidence ADC and BEC respectively. Thus we find that these parallel rays are reflected from the mirror to meet at the point F. Such a point where rays meet is called a *focus*. With a convex mirror, the reflected rays are divergent, but they seem to meet at a point back of the mirror. Such a point is a *virtual focus*. If the aperture of the mirror is small, rays of light parallel to the principal axis will meet or appear to meet at the *principal focus*, which is a point *midway between the center of curvature and the vertex*. The distance FV from the principal focus to the vertex is called the *focal length of the mirror*.

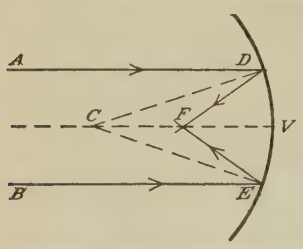


FIG. 433. — Parallel rays are reflected to principal focus.

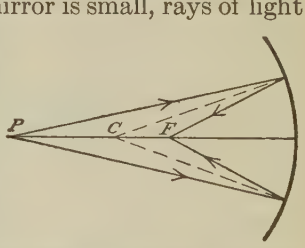


FIG. 434. — Divergent rays are reflected as shown.

Diverging rays coming from a point P on the principal axis will be brought to a focus on the principal axis, but the focus will be nearer the center of curvature than it is to the mirror. (See Fig. 434.) *Converging* rays are also focused by curved mirrors. Fig. 435 shows a case where they are focused upon the principal axis between the vertex and the principal focus.

386. Construction of the Image of a Point in a Spherical Mirror. To construct the image of point P formed by a concave mirror. Draw the principal axis. (See Fig. 436.) Since light is given off in all directions from the point P, we may draw *any two* lines incident upon the mirror and find where they intersect after reflection. In all construction work care must be taken to make the angles of incidence and reflection equal. It is easier to use for one line the secondary axis, since it is incident upon the mirror at an angle of 90° and it is reflected directly back upon itself. *The image of a point is always some place on its secondary axis.* Let us draw the secondary axis PS from P to the mirror. The image of P will lie at some point on PS. Since all rays *parallel* to the principal axis are reflected back through the principal focus, the next easiest line to trace is one parallel to the principal axis. Draw PB parallel to the principal axis, and then the reflected ray BF through the principal focus. The image of P is some place on BF. But P' is the only point common to PS and BF; therefore the image of P is formed at P'. To prove that PB passes through F by reflection, draw the normal BC. If the work has been accurately done, the angles PBC and CBF will be equal.

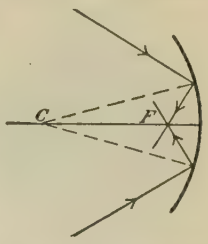


FIG. 435.— Converging rays meet nearer the mirror than principal focus.

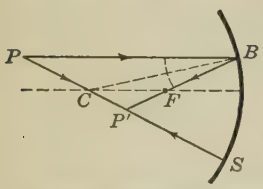


FIG. 436. — Image of point formed by curved mirror.

387. How Images Are Formed by Concave Mirrors. It will be of interest to study the formation of images by concave mirrors. We may first think of an object at an infinite distance from the mirror, and then study the different images formed by the mirror as the object approaches it. Thus six quite distinct cases may be studied: first when the object

is at an infinite distance, then at a measurable distance beyond the center of curvature, next when it is at the center of curvature, when the object is between the center of curvature and the principal focus, when it is at the principal focus, and finally when it is between the principal focus and the vertex.

Fig. 438. — Optical disc. Reflection from concave mirror.

Case 1. In Fig. 437, we have several rays of light incident upon the mirror, all parallel to the principal axis. This is exactly what would happen if an object were at an infinite distance, since all the rays coming from such an object would be parallel. All these rays are reflected back to the principal focus. The image formed is a point. Hence we conclude that *the image is a point at the principal focus, when the object is at an infinite distance from a concave mirror.* (See Fig. 438.)

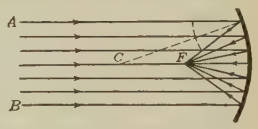



Fig. 437. — Object at infinite distance. Case 1.

Case 2. In Fig. 439 we have the object AB at a finite distance beyond the center of curvature. We find the image of the point A by drawing the secondary axis AC and the parallel ray AD, which is reflected back through F to form the image of A at A'. In a similar manner we locate the image of B at B'. We shall number all the construction lines used to locate A' as 1; those used to locate B', we shall number 2. We see that the *image is real, inverted, smaller than the object, and it is formed between the center of curvature and the principal focus, provided the object is at a finite distance farther from the mirror than its center of curvature.* The nearer the

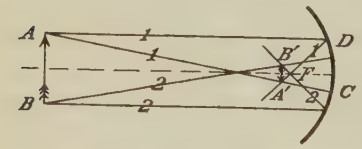


Fig. 439. — Two lines are necessary to locate image.

object approaches the center of curvature, the larger the image becomes.

Case 3. When the object is at the center of curvature, as in Fig. 440, we find that the image of A is formed at A', a point coincident with B, and the image of B is formed at B'. The secondary axes are not shown in this figure, since the aperture of the mirror would need to be 180° to include them. *When the object is at the center of curvature, the image is real, inverted, the same size as the object, and located at the center of curvature.*

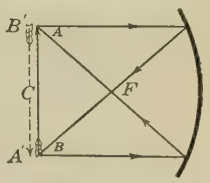


Fig. 440. — Object at center of curvature. Case 3.

Case 4. This case is the converse of Case 2. From Fig. 441, we see that the object is placed between the center of curvature and the principal focus. The image is formed beyond the center of curvature; it increases in size as the object approaches F. Hence *when the object is between the center of curvature and the principal focus, the image is real, inverted, larger than the object, and beyond the center of curvature.*

Case 5. In this case the object is at the principal focus. It is the converse of Case 1. If we try to construct the image

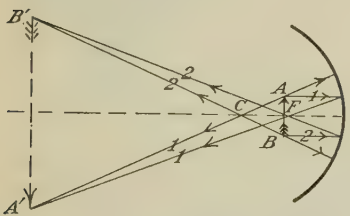


Fig. 441. — Object between center of curvature and principal focus.

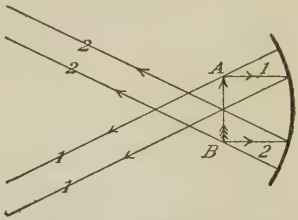


Fig. 442. — Object at principal focus.

as in the other cases, we find that the reflected rays are parallel. *When the object is at the principal focus, no image is formed.* (See Fig. 442.)

Case 6. Let us place the object between the principal focus and the mirror and construct the image as in the preceding cases. We find that the reflected rays are divergent; hence they cannot form a real image. These rays *appear to meet behind the mirror to form a virtual image.* (See Fig. 443.) *When the object is between the principal focus and the mirror, the image is virtual, erect, enlarged, and behind the mirror.*

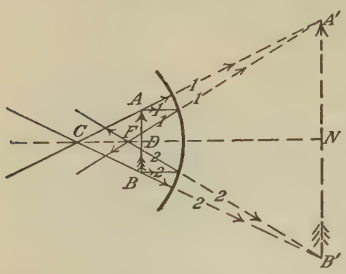


Fig. 443. — Object between principal focus and mirror.

388. Images Formed by Convex Mirrors. If we look into a convex mirror of the type used on automobile fenders, we see an erect image of reduced size. We may use a diagram to show how such an image is formed. In Fig. 444, AB represents the object. The secondary axes are the radii produced. The parallel rays are reflected from the convex surface and made divergent. Hence they cannot meet to form a real image. They seem to meet behind the mirror to form a virtual image as shown by the dotted lines. The optical disc of Fig. 445 shows how parallel rays of light are scattered by a convex mirror. As the object is brought nearer the mirror, the image increases in size, becoming almost as large

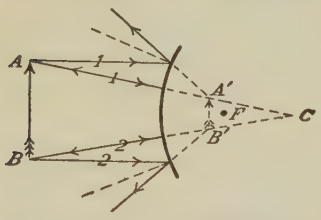


Fig. 444. — Image formed by convex mirror.

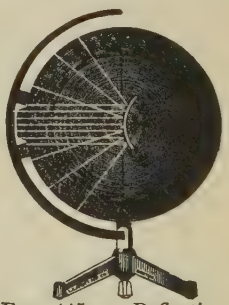


Fig. 445. — Reflection from convex mirror.

as the object when it is very near the mirror. In all cases, *the images formed by convex mirrors are virtual, erect, smaller than the object, and between the mirror and the principal focus.*

389. Applications of Curved Mirrors. Sometimes peculiarly curved mirrors are used in amusement parks to form distorted images. The convex mirror, which is sometimes used on automobiles, gives a wide field of vision, but the driver cannot judge how close an approaching car is by the position of the image in the mirror.

Concave mirrors are used as reflectors of light and also for forming images. Cases 1 and 3 may be used to find the focal length of the mirror. Since *the focal length is just one half the radius,* we may double the focal length to find the radius of curvature. By the use of Cases 2 and 4 images may be thrown upon a screen. The former gives a bright image of reduced size, while the latter gives an enlarged image. When an image is enlarged, it loses in brightness. Case 6 is an application of the so-called shaving mirror. Your dentist uses a small mirror of this type in examining your teeth.

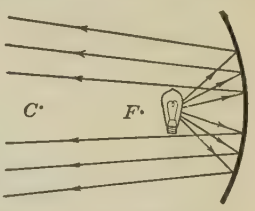


FIG. 446. — Headlights and searchlights.

If we place an electric light at the principal focus of a concave mirror, its rays will be reflected from the mirror along parallel lines. When the light is placed a little nearer the mirror than the principal focus, the rays will be slightly divergent, as shown in Fig. 446. Such a reflector is used in the headlights for automobiles, street-cars, and locomotives. The searchlight and spotlight may use a concave mirror, or lenses may be used to concentrate the light rays on a distant object.

Fig. 447 shows how different types of reflectors may be used to secure a proper distribution of light. Some reflectors are wide and flaring. Others of the bell-shaped type concentrate the rays on a smaller area.

The *ophthalmoscope* is a small concave mirror with a hole in its center. By using this instrument, a physician can reflect light into a patient's eye, and at the same time look into the eye through the hole in the mirror.

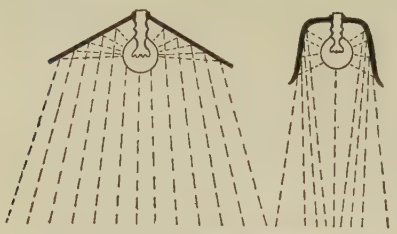


Fig. 447. —Type of reflectors.

390. Spherical Aberration. Only those parallel rays of light which are incident upon a curved mirror near its vertex are reflected back to the *principal focus*. The rays which fall upon the edge of the mirror, or near the edge, are focused nearer the mirror than the principal focus. (See Fig. 448.) Such a *wandering of the focus* produces a distorted image. Such non-focusing of parallel rays at the principal focus is called *spherical aberration.*

To remedy this defect in mirrors, several methods are in use. If the aperture of the mirror can be kept within 10° or

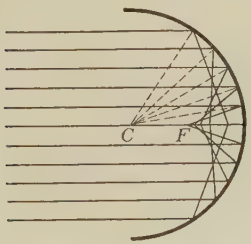


Fig. 448. — Spherical aberration.

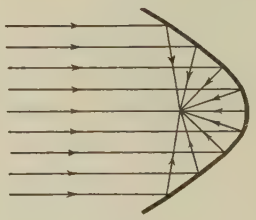


Fig. 449. — Parabolic mirror.

12°, the distortion of the image is negligible. A mirror of larger aperture may be used to gather more light rays, but an annular diaphragm made of some opaque material should be used to cut off those rays that would be incident near the edge of the mirror. An adjustable diaphragm is used with a camera lens in a similar manner. One of the best methods

of preventing spherical aberration is to use a mirror whose surface is not a sphere, but has the curve of the parabola. Fig. 449 shows how parallel rays are all focused at a point by such a mirror. Headlights in automobiles are usually fitted with parabolic reflectors.

391. Relative Size of Object and Image. In § 380 we found that the relative size of the object and image depends upon their respective distances from the aperture. This was shown by the use of similar triangles. In the same manner, it is possible to show that the sizes of the object and the image formed by a curved mirror depend upon their relative distances from the center of curvature. (See Fig. 443.) For mirrors of small aperture, it is possible to show that the relative *sizes of the object and image depend upon their respective distances from the mirror.* Stated as a proportion, size of object (S_o) : size of image (S_i) = distance of the object from the mirror (D_o) : distance of image from mirror (D_i). Or, $S_o : S_i = D_o : D_i$. Of course when an object is magnified or reduced in size, both the length and the breadth are changed proportionally.

PROBLEM. An object 8 inches high is placed 3 ft. from a mirror. The image is formed on a screen 18 in. from the mirror. Find the height of the image.

Solution. By substituting in the formula, $S_o : S_i = D_o : D_i$, we have, $8 : x = 36 : 18$. Whence, $x = 4$ in., the height of the image.

392. Distances of Object and Image in Terms of the Focal Length. As one might suspect from the various cases of image formation by concave mirrors, there is a mathematical relation between the distances of the object and image from the mirror and the focal length of the mirror. The derivation of such a formula is beyond the scope of secondary school work, but the formula is useful for solving problems. Using D_o to represent the distance of the object from the mirror,

D_i to represent the distance of the image from the mirror, and F for the focal length, then

$$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{F}.$$

This formula may be used in all cases governing concave mirrors. When the answer is a negative quantity, the image is virtual.

For convex mirrors, both $\frac{1}{D_i}$ and $\frac{1}{F}$ are negative.

PROBLEM. An object is 6 ft. from a mirror whose focal length is 8 inches. Find the distance from the mirror at which the image is formed.

Solution. Substituting in the formula $\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{F}$, we have the following: $\frac{1}{72}+\frac{1}{D_i}=\frac{1}{8}$. Clearing of fractions, $D_i+72=9D_i$. Whence $D_i=9$ in.

SUMMARY

The angles of incidence and reflection are equal, and they lie in the same plane.

Reflection from a polished surface is regular; from a rough surface, it is irregular or diffused.

Mirrors are plane or spherical; spherical mirrors may be concave or convex.

Images are real or virtual; a real image is inverted and can be thrown upon a screen. Virtual images are erect; they cannot be thrown upon a screen.

Images formed by plane mirrors are erect, virtual, the same size as the object, and as far behind the mirror as the object is in front.

A focus is a point where rays of light meet or from which rays of light diverge. Rays parallel to the principal axis are reflected to a point on the principal axis, midway between the center of curvature and the vertex. This point is the principal focus. Its distance from the vertex is the principal focal length. It equals half the radius of curvature of a concave mirror.

In concave mirrors the image is a point when the object is at an infinite distance. As the object approaches the mirror, the real image formed increases in size, becoming equal to the object at the center of curvature, and infinitely large at the principal focus. If the object is brought nearer the mirror than the principal focus, the image becomes virtual.

The images formed by convex mirrors are erect, virtual, and smaller than the object.

Spherical aberration is the deviation from the principal focus of those rays of light that are reflected from the edge of the mirror. It may be remedied by using a diaphragm, or by having the mirror shaped like a parabola.

QUESTIONS

1. Why can we look at the image of the sun in the water at noon, but not in the afternoon when the sun is low on the horizon?

2. Given two plane mirrors. Draw a diagram to show how a person on the north side of a house could use them to see a person on the south side.

3. What advantages does a plane mirror used as a driver's mirror have over a convex mirror? What advantages does a convex mirror have over a plane mirror?

4. Draw a diagram to show how two small mirrors can be placed in a tube to enable one of short stature to see over the heads of other persons in a crowd.

5. Explain how a too glaring headlight may be remedied.

6. The law of New Jersey specifies that no headlight may cast a beam of light that is higher than 4 ft. at a distance of 200 ft. In what two ways could you adjust a headlight that did not meet this legal requirement?

7. The manufacturing companies have stopped making electric bulbs of clear glass. Give a good reason.

8. The maximum candle power of a tungsten lamp is horizontal. In what way may this defect be remedied?

9. Why is the image formed by the bowl of a silver spoon distorted?

10. Lay a plain gold ring on a sheet of white paper. Note the shape of the image that is produced. How does this image, which

is called the "caustic by reflection" illustrate spherical aberration? Compare this image with that formed by the inside surface of a glass of water resting on a white tablecloth when the light is strong.

11. What changes would one observe in his image as he approached: 1. A plane mirror? 2. A convex mirror? 3. A concave mirror?

12. Usually 21-C.P. bulbs are used in automobile headlights. Do you think the law of inverse squares applies to the light from such a headlight? Explain.

PROBLEMS

1. A man runs toward a plane mirror at the rate of 10 feet per second. At what rate does he approach his image?

2. Given a room 20 ft. square. For general illumination, which would be better, an 80 C.P. lamp placed in the center or four 20 C.P. lamps, one four feet from each corner. Give two reasons for your answer.

3. An object is 4 ft. from a concave mirror whose focal length is 9 inches. How far away is the image? If the object is 2 ft. high, calculate the height of the image.

4. An object is 8 in. from a concave mirror whose focal length is 12 in. How far from the mirror is the image formed? How many times is the image magnified?

5. A pin-hole camera has a sensitive plate 4×4 in. The box is 6 in. long. How far away must a man 6 ft. tall stand for a full-length image to be formed?

6. An object is placed 12 in. from a concave mirror whose focal length is 10 in. How far from the mirror is the image? What is the relative size of object and image?

7. A concave mirror has a focal length of 15 in. The object is placed 12 in. from the mirror. How far away is the image?

8. The radius of a concave mirror is 36 in. An object is 12 ft. away from the mirror. Where is the image formed? How tall is the image, if the object is 4 ft. high?

CHAPTER 18

LIGHT—REFRACTION

Vocabulary

Binocular, employing both eyes at once.
Refraction, the bending of rays of light which pass obliquely from one medium into another of different optical density.

393. Refraction. When we fire a rifle at some object in the air, we are making use of the fact that light travels in straight lines. If, however, we should try to shoot a fish in the water, we would learn that light rays are bent as they pass from air into water or vice versa. Fishes appear to be higher in water than they really are, thus making it difficult to shoot or spear them. It is also well known that water is deeper than it really appears. When we step in the water on an uneven sidewalk or in the gutter, we find that it is considerably deeper than it seems. If we look down into a tall cylinder of water and put a finger on the outside of the jar where the bottom appears to be, we find that it is only three fourths of the way down. A stick or a teaspoon placed in a glass of water appears to be bent or broken at the surface.

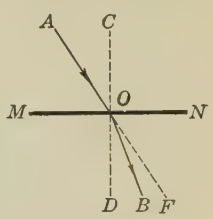


FIG. 450. — Refraction of light.

From the preceding examples, we conclude that light rays bend as they pass obliquely from one medium into another of different optical density. Such bending of light rays is known as *refraction.* In Fig. 450, we may use MN to represent the surface of a body of water, and AO as a light ray traveling through the air and incident upon the water sur-

face at the point *O*. Instead of continuing along the line *OF* in a straight line, it is bent as it passes from air into water and takes the path *OB*. The angle *AOC* is called the *angle of incidence*. The angle *DOB*, which is the angle that the refracted ray makes with the normal, is called the *angle of refraction*. The angle *BOF* is the *angle of deviation*. There is one exception which the student must remember. A ray of light incident upon a medium of different optical density *at a right angle*, or *along the normal, is not refracted*.

394. Cause of Refraction. Suppose we have five men marching abreast over a hard road. (See Fig. 451.) Their line of march, *AB*, carries them over a strip of marshy ground where their speed is retarded. The man at *R* enters the marsh land first and is the first to be retarded. Since the others continue at the same speed as before, the line of march now takes the direction *BC*. In the marshy ground all are equally retarded until the man *R* reaches harder ground and his speed increases. The line of march now takes the direction *CD*. The student will observe that as the speed decreases the line bends toward the perpendicular. An increase of speed on entering a new medium causes the line to bend away from the normal. It is evident that if the line of march were along the perpendicular, all would enter the marshy ground at once; they would therefore all be retarded at the same time and the line of march would not be bent. A dumbbell rolled across the floor will travel in a straight line, unless one of the balls is retarded more than the other; then it will be turned out of

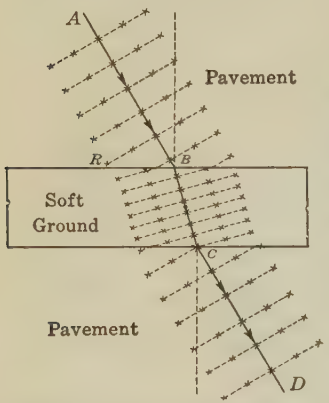


FIG. 451. — Cause of refraction.

its course. If the right front wheel of an automobile which is going in a straight line enters a strip of soft ground, the wheels will turn, and the car will swerve to the right since the right front wheel is retarded.

Light travels more slowly in water than it does in air. Now we may picture a ray of light as having some thickness. Hence the edge of the ray which is first incident upon the water is the first to be retarded, and the ray is bent out of its course. Of course such bending will occur when the light enters any medium of greater optical density, in which the speed is retarded. The bending will occur in the opposite direction, if the speed in the new medium is accelerated. Light rays incident upon the medium at an angle of 90° are all retarded or accelerated equally. Hence there is no bending.

395. Index of Refraction. Fizeau and Foucault, two French physicists, were the first to make direct measurements of the velocity of light in air. In 1850, Foucault proved that light travels faster in air than it does in water. The speed of light in water is almost 140,000 miles per second, just $\frac{3}{4}$ as fast as in air. The speed of light in ordinary glass is about 124,000 miles per second, only about $\frac{2}{3}$ the velocity of light in air. *The ratio of the speed of light in air to its speed in another substance is called the index of refraction for that substance.* For example, the index of refraction for glass equals $\frac{\text{speed in air}}{\text{speed in glass}}$. The value for glass is $\frac{3}{2}$, or 1.5. Since the speed of light in water is only three fourths as great as in air, the index of refraction of water is $\frac{4}{3}$, or 1.333. The index of refraction of a few substances is given in the following table:

Alcohol . . . 1.36	Diamond . . 2.47	Olive oil . . 1.47
Canada balsam . 1.52	Glass, crown . 1.52	Opal . . . 1.45
Cotton seed oil . 1.47	Glass, flint 1.54–1.94	Water . . . 1.33
Carbon disulphide 1.62		

The index of refraction may also be defined as the ratio of the *sine* of the angle of incidence to the *sine* of the angle of refraction. Let us refer to Fig. 452. In the right triangle, ABC, the sine of the angle BAC is defined as the ratio of the length of the side a, opposite the angle BAC, to the hypotenuse c. Enlarging the triangle without changing the size of the angle BAC does not affect this ratio, since the quotient of $\frac{a'}{c'}$ exactly equals that of $\frac{a}{c}$. A table of sines for the angles from 0 to 90° is given in Appendix C.

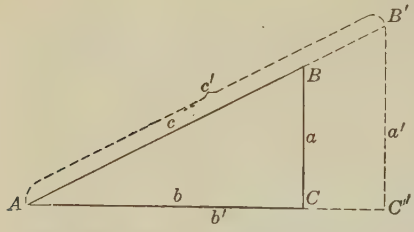


Fig. 452. — Sine of an angle is the ratio of side opposite the angle to the hypotenuse.

In Fig. 453, the line AO represents a ray of light traveling through the air and incident upon a glass plate at O. This ray is refracted as it enters the glass and moves along the path OB. To find the index of refraction, we first draw the normals OP and OP'. The index of refraction between the air and the glass is equal to the sine of the angle AOP divided by the sine of the angle BOP'.

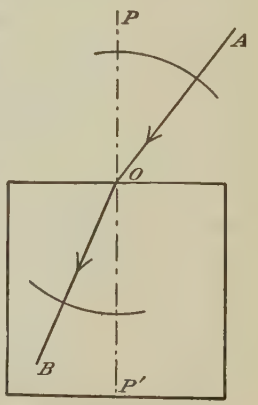


Fig. 453. — The index of refraction.

396. Applications. Since transparent substances have a constant index of refraction, the measurement of the index furnishes a convenient method for their identification. An instrument, called a *refractometer*, has been so constructed that the index can be measured quickly and accurately. Butter fat and oleomargarine have different indices of refraction. This

difference furnishes one of the tests used to distinguish butter from oleomargarine. The exceedingly high index of refraction of the diamond furnishes an excellent method of identifying it. Other gems may be identified by their refractive indices.

397. Laws of Refraction. Some of the facts which we have learned in the preceding sections may be summarized as the LAWS OF REFRACTION. We observed that the speed is reduced when light passes from a rarer to a denser medium, and that the speed is increased as it passes from a denser to a rarer medium.

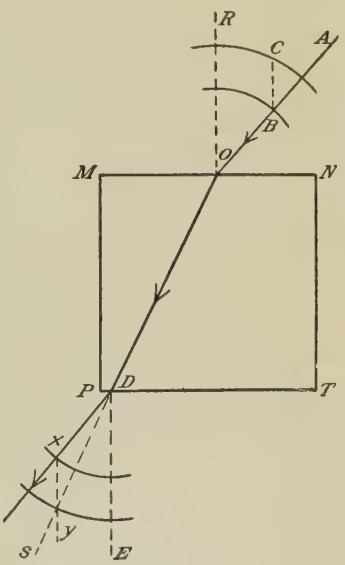


FIG. 454. — How we trace a ray of light through glass.

LAW 1. *When a ray of light passes obliquely from a medium of lesser to one of greater optical density, it is bent toward the normal.* (A decrease in speed.) Conversely, *a ray of light passing obliquely from a denser to a rarer medium is bent from the perpendicular to the surface.* (An increase in speed.)

LAW 2. *The angles of incidence and refraction lie in the same plane.*

LAW 3. *The index of refraction for any two media is constant, no matter what the angle of incidence.*

398. Tracing a Ray of Light Through Glass. If we know the index of refraction, it is possible to show the path that a ray of light takes as it passes through another medium. In Fig. 454, we may let *MNTP* represent a piece of plate glass and *AO* a ray of light incident upon the plate. From *O* as a

center, let us describe two arcs having the ratios 3 and 2, the index of refraction of glass. Draw the normal OR, and the line BC parallel to it, passing through the point where the incident ray intersects the *smaller* arc. The line OD which is determined by the points C and O marks the path taken by the refracted ray as it travels through the glass.

If the ray were not refracted as it leaves the glass, it would pass along the line DS. To show how it is refracted, from D as a center we draw arcs having the same ratio as before. Draw the normal DE, and a line xy parallel to the normal. This time we draw the parallel line through the point where the *larger* arc is intersected by the refracted ray *produced*. The line Dx shows the path the refracted ray takes as it leaves the glass.

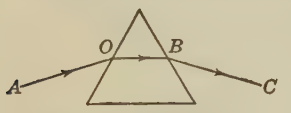


FIG. 455. — Path of ray through prism.

As the ray of light AO is incident upon a triangular glass prism, as shown in Fig. 455, it is bent toward the perpendicular, and travels along the line OB. As the light leaves the prism, it is refracted from the perpendicular along the line BC.

399. Atmospheric Refraction. Light travels somewhat faster in a vacuum than it does in air. As the light approaches us from the sun or the stars, it will be refracted as it enters the earth's atmosphere. But since the light enters an atmosphere that gradually grows denser and denser, a ray of light coming from the sun or some other celestial body follows a path similar to the curve shown in Fig. 456. The refraction is gradual, instead of one distinct bend at the inter-surface of the two media.

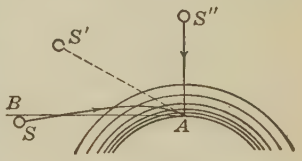


FIG. 456. — Ray through atmosphere.

On account of atmospheric refraction, we do not see the

sun or stars in their true positions except when they are directly overhead at the zenith. We see the sun in its true position at noontime, if its rays are vertical. In the figure, we see the setting sun at S', instead of in its true position at S. The refraction of light by our atmosphere makes the sun at this time appear about one diameter higher than it really is. Since the index of refraction from ether to air is only 1.00029, naturally the diagram must be greatly exaggerated to show on so small a scale any bending at all.

400. Critical Angle and Total Reflection. Since a ray of light in passing from a denser to a rarer medium is bent *from* the perpendicular, it will be of interest to inquire what happens as we increase the angle of incidence. Suppose we let Fig. 457 represent rays of light passing from water into air. When we start with a small angle of incidence, AOC, the refracted ray is OB. By making the angle of incidence greater, a point is finally reached where the refracted ray does not enter the air at all but takes the direction ON, coincident with the surface. Between water and air, this occurs when the incident ray DO makes an angle of 48.5° with the normal. *That particular angle of incidence at which the refracted ray makes an angle of 90° with the normal is called the critical angle.* The critical angle for crown glass is 42°; for the diamond it is only 24°.

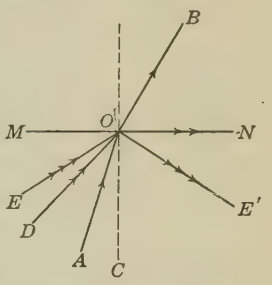


FIG. 457. — Critical angle.

When we increase the angle of incidence beyond the critical angle, as at EOC for example, then the ray of light is reflected along the path OE'. There is no refraction at all, since all the light is turned back into the water medium. This is *total reflection,* which occurs whenever the angle of incidence exceeds the critical angle. Of course the angle of reflection equals the angle of incidence. When the critical

angle is small, as in the diamond, much of the light is reflected. The diamond is the most brilliant of gems. All the light that enters it, except within the narrow cone of 48°, undergoes total reflection. By setting the diamond in platinum, which is also a good reflector, its brilliancy is enhanced.

401. Applications of Total Reflection. We have just learned that the brilliance of the diamond is largely due to total reflection. Cut-glass is made from glass having a high index of refraction in order to increase the amount of light it reflects. When a ray of light enters a right-angle glass prism like that shown in Fig. 458, it is totally reflected. The periscope of a submarine has two such prisms. The observer at D sees objects along the line AB. The light rays are reflected down the tube by the first prism. The second prism again changes the direction by total reflection. The right-angle prism is more efficient as a reflector than a mirror would be if set in the same position. In the Zeiss binocular, a very good field glass, such prisms not only give a wider range of vision, but they also reinvert the image, making it erect. The reflecting telescope, and the range-finder used on battleships, also make use of total reflecting prisms.

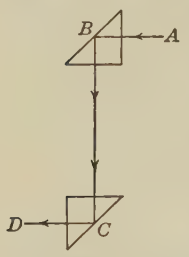


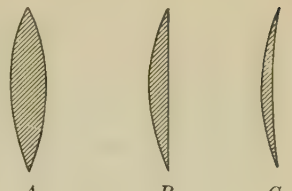
FIG. 458. — Total reflecting prism. Periscope principle.

402. Lenses. In § 398 we learned that light rays are bent in passing through a prism. We may use lenses in a similar manner to refract light rays and also to focus them. A portion of any transparent substance can be used as a lens. It must be bounded by two non-parallel curved surfaces or by one curved and one plane surface. Lenses are practically always made of glass.

Converging lenses are always thicker in the middle than at the edges. Three different types of such lenses are shown in Fig. 459. The first two examples are called flat lenses; the

third one is a meniscus lens. They are much used by persons who are far-sighted.

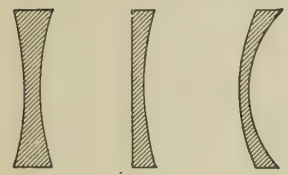
Diverging lenses are thicker at the edges than they are in the middle. Three different kinds are shown in Fig. 460. The double concave and the single concave lenses are also examples of flat lenses, while the convexo-concave lens is a meniscus lens. They are used to correct near-sightedness.



A. *B.* *C.*

FIG. 459. — Converging lenses. *A.* Double-convex. *B.* Plano-convex. *C.* Concavo-convex.

403. How Lenses Affect Light. When a ray of light is incident upon the center of a lens it passes through the lens without being refracted at all. If it passes through any other part of the lens it is bent out of its course. Fig. 461 shows how rays of light are bent toward the normal as they enter a double convex lens, and are refracted from the normal as they leave the lens. The ray AD, for example, is bent at D as it enters the lens, and at E when it leaves the lens. *Parallel rays of light are brought to a point at the principal focus by such a lens.* All converging lenses behave in a similar manner. If converging rays of light are incident upon such a lens, they converge to a point more quickly, and are brought to a focus at a point nearer the lens than the principal focus. If the rays are diverging when they fall upon the lens, they are made less divergent. Very divergent rays cannot be brought to



A. *B.* *C.*

FIG. 460. — Diverging lenses. *A.* Double-concave. *B.* Plano-concave. *C.* Convexo-concave.

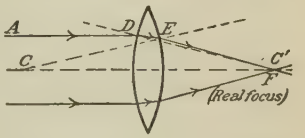


FIG 461. — How converging lenses focus parallel rays.

a *real* focus, but slightly divergent rays may be focused at a point beyond the principal focus.

Diverging lenses tend to scatter the rays of light, as shown in Fig. 462. Parallel rays are made divergent; they seem to meet to form a *virtual* focus, as shown by the dotted lines. Converging pencils of light have their convergence decreased by such lenses. The divergence of diverging pencils is increased.

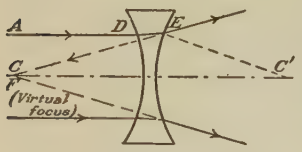


Fig. 462. — How diverging lenses focus parallel rays.

404. Definition of Terms. Before we can study the formation of images by lenses, a few definitions must be mastered. In many lenses, there are two *centers of curvature, CC′.* (See Fig. 463.) In this case they are the centers of the intersecting spheres that form the lens. The *principal axis* passes through the centers of curvature. The ray of light *AB* is refracted and passes through the principal focus *F*. *In lenses the secondary axes pass through the optical center of the lens;* the optical center *O* practically coincides with the geometrical center of the lens. The ray *AOA′* is an example of a secondary axis drawn from *A*. Rays of light passing through the optical center *are not refracted.*

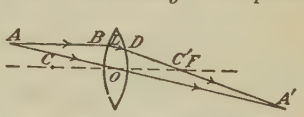


Fig. 463. — Terms defined.

Similar to curved mirrors, lenses refract parallel rays so that they meet at the *principal focus,* but this focus is *not midway* between the lens and the center of curvature. Its position on the principal axis will depend upon the index of refraction of the lens. With a double convex lens of crown glass, the principal focus and the center of curvature are almost coincident. With such a lens, the radius of curvature and the *principal focal length* are almost equal. Increasing the index of refraction shortens the focal length. The thicker

the lens, the shorter the focal length, but in this case the radius of curvature is also reduced.

405. How Lenses Form Images. By a study of Fig. 463, we may learn how images are formed by lenses. CC' represent the centers of curvature of the lens L. We wish to show how the image of the point A is formed. Here again, it will be necessary to use two rays coming from A and see how they are focused by the lens. For one ray of light, we may choose the secondary axis, since it is not refracted as it passes directly through the optical center, O. For the other ray we may select AB, parallel to the principal axis. At B this ray is refracted, being bent again as it leaves the lens at D and passes through the principal focus F, which is coincident with C'. Thus we locate the image of A at A' where the ray refracted through the principal focus meets the secondary axis, AA'.

The student must keep in mind several differences between lenses and mirrors. 1. Secondary axes pass through the optical centers of lenses, but not through the centers of curvature. 2. The principal focus is at or near the center of curvature; this makes the focal length practically equal to the radius, whereas in mirrors it is equal to half the radius. 3. Since the image is formed by rays of light that pass through the lens, a *real* image is formed on the opposite of the lens from the object, just the reverse from mirrors. *Virtual* images formed by lenses appear to be on the same side of the lens as the object. 4. Convex lenses form images in almost the same manner as concave mirrors; concave lenses are like convex mirrors in the manner in which they form images.

406. Images by Convex Lenses. Just as with concave mirrors, we may consider six cases for the formation of images by convex lenses, considering that the object is brought forward from an infinite distance toward the lens by several successive steps.

Case 1. We have all used a lens as a burning glass. Just as the heat rays from the sun are focused at a point, so are the light rays. We may consider that all the parallel rays from the sun that are incident upon the lens are refracted so they will meet at the principal focus. *When the object is at an infinite distance, the image is a point at the principal focus.* The optical disc of Fig. 464 shows how parallel rays are focused. This case has no practical value for image formation. It may be used *to find the focal length of the lens.* When the sun's rays are focused on a white screen, the distance from the lens to the screen is the focal length of the lens.

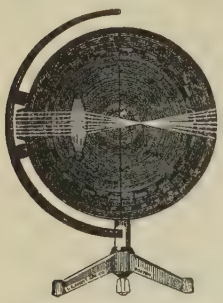


Fig. 464. — Refraction of parallel rays by convex lens.

Case 2. Let us use Fig. 465 to show how a lens forms images when the object is distant from the lens *more than twice* its focal length. Drawing the secondary axes from A and from B and also parallel rays from each point, we find that they meet on the opposite side of the lens to form the

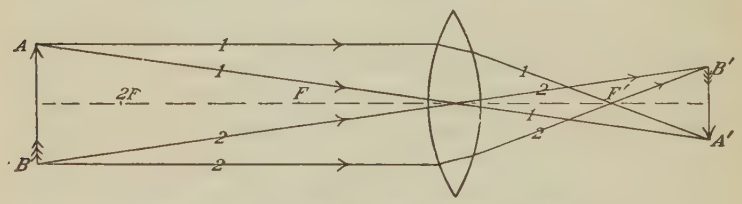


Fig. 465. — Object at finite distance. Case 2.

image $A'B'$. Hence we conclude that *when the object is at a finite distance more than twice the focal length of the lens, the image is real, inverted, and smaller than the object.* The image is distant from the lens more than once and less than twice its focal length. The lenses of the eye, the camera, and the

telescope, where small, bright, well-defined images are needed, are all applications of this case.

Case 3. Just as we constructed the image in § 405, so we may construct the image for this case. From Fig. 466 we see that *when the object is at a point just twice the focal length of the lens, the image is real, inverted, the same size as the*

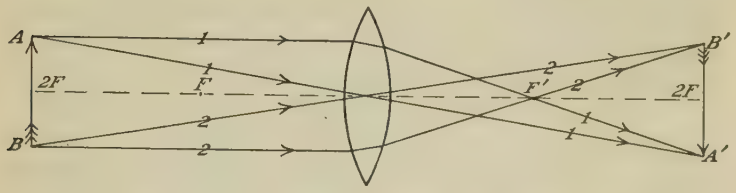


Fig. 466. — Object distance twice the focal length. Case 3.

object, and at a distance equal to just twice the focal length. If we wish to turn an inverted image upside down so that we may see it erect, as with the field telescope, this case is applicable.

Case 4. *When the object is distant more than once and less than twice the focal length, the image is real, inverted, enlarged, and distant from the lens more than twice its focal length.* Of

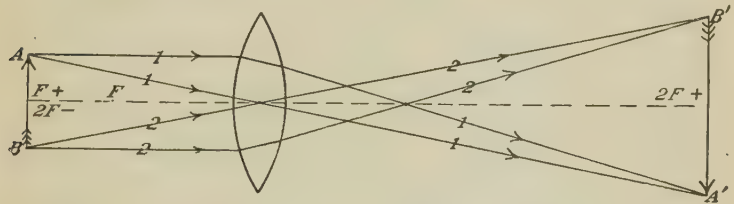


Fig. 467. — Object between *F* and *2F*. Case 4.

course this case is the converse of Case 2. We use it when we wish to produce a magnified, real image. The compound microscope, the optical lantern, and the motion picture machine are illustrations. (See Fig. 467.)

Case 5. *When the object is at the principal focus, the rays of light are parallel as they leave the lens, and no image is formed.* If we place a light at the principal focus, its rays leave the lens as a beam of light. The lighthouse and the searchlight are applications of its use. (See Fig. 468.)

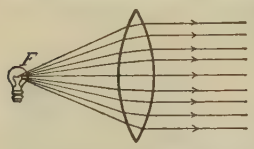


Fig. 468. — Object at *F*. Rays are parallel. Case 5.

Case 6. *When the object is nearer the lens than the principal focus, the image is virtual, erect, enlarged, and on the same side of the lens as the object.* The rays of light are diverging as they leave the lens; hence they cannot form a real image. If the eye is placed close to the lens, the enlarged image can be seen, but it can never be thrown on a screen. The simple magnifier is an application. (See Fig. 469.)

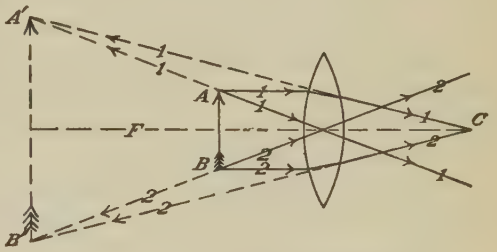


Fig. 469. — Object between lens and *F*.

407. Images Formed by Concave Lenses. The optical disc of Fig. 470 shows that concave lenses scatter light rays. The only kind of image such a lens can form is a virtual one. The image is always erect and smaller than the object. Such a lens may be used to neutralize the effect of a convex lens, or of one that is too convex.

408. Spherical Aberration. When we use a camera on a bright day we nearly close the diaphragm so that light can pass through the central part of the lens only. This gives an image that is well-defined. On a darker day we open the diaphragm more to let in more light. The image is not so distinct and clear-cut, since the rays of light that pass through

a lens near the edge do not meet quite at the principal focus. Spherical aberration is a defect of lenses just as it is of spherical mirrors. (See Fig. 471.)

The diaphragm is used to correct spherical aberration in lenses. With the camera it is adjustable. The lens may be so ground that its surface has the shape of a parabola. A lens that is corrected for spherical aberration in this manner may be used with the diaphragm wide open. Such lenses are known as "high-speed" lenses.

FIG. 470. — Refraction of parallel rays by concave lens.

409 Size of Image and Object. We may use the same formula to find the relative sizes of object and image with respect to their distances from a lens that we did for curved mirrors. The letters S_o and S_i in the following formula represent the sizes of object and image, while D_o and D_i represent the distances respectively of object and image from the optical center of the lens.

$$S_o : S_i = D_o : D_i.$$

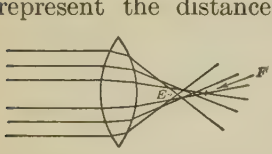


FIG. 471. — Spherical aberration.

410. Distance of Object and Image as Related to Focal Length. We may use the same formula that we used with curved mirrors when we wish to find the distance of the object and image from a lens in relation to its focal length. If we use D_o to represent the distance of the object from the lens, D_i to represent the distance of the image from the lens, and F to represent the focal length of the lens, then we have the following formula:

$$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{F}.$$

When the answer is a negative one, the image is virtual. For concave lenses, both $\frac{1}{D_i}$ and $\frac{1}{F}$ are negative.

SUMMARY

Refraction is the bending of a ray of light out of its course as it passes obliquely from one medium into another of different optical density. When passing into a more highly refractive medium, it is bent toward the perpendicular and conversely.

The index of refraction of any substance is the ratio of the speed of light in air to its speed in that substance.

That especial angle of incidence at which the refracted ray is perpendicular to the normal is called the critical angle. Total reflection occurs when the angle of incidence exceeds the critical angle.

In the manner in which they form images, convex lenses are analogous to concave mirrors; concave lenses are analogous to convex mirrors.

Spherical aberration, which occurs in lenses as well as in mirrors, may be remedied by the use of a diaphragm.

QUESTIONS

1. Give two reasons why the sun is visible after it sinks below the horizon.

2. In making microscopic slides Canada balsam is used to cement the cover glass to the slide. Give a good reason why Canada balsam is used.

3. Flint glass is used in making cut-glass. What advantage has it over crown glass?

4. What effect would immersion in water have upon the focal length of a convex lens?

5. Draw a diagram to show how a lantern must be constructed to throw a beam of light in one direction only.

6. Objects are practically invisible when immersed in a liquid that has the same index of refraction. How can carbon disulphide be used to distinguish between real diamonds and paste diamonds, which are made of flint glass.

7. Give one reason why you would expect to see the sun before it rises above our horizon and one reason why you would not expect to see it for a few minutes after it has risen.

PROBLEMS

1. How fast does light travel in the diamond? What is its speed in crown glass? What is its velocity in flint glass? (Index of refraction, 1.65.)

2. If the speed of light in a transparent medium is 105,000 miles per second, what is the index of refraction of that medium?

3. A candle is 8 ft. from a double convex lens of 8 in. focal length. How far away from the lens is the image formed? What is the height of the image, if the object is 12 in. tall?

4. An object placed 80 cm. in front of a double convex lens forms a distinct image on a screen 25 cm. on the other side of the lens. What is the focal length of the lens?

5. An object is 30 cm. in front of a convex lens whose focal length is 50 cm. How far away is the image formed? How does it compare in size with the object?

6. A convex lens has a focal length of 15 cm. An object is 20 cm. from the lens. How far from the lens is the image formed? If the object is 30 cm. high, how tall is the image?

7. A picture is 5×6 in. What is the size of the image of this picture if it is placed 9 in. from a convex lens of 8 in. focal length?

8. The image of an object 4 ft. high is formed on a screen 3 in. high. How far away must the object be placed from the lens to form a full-length image on the screen, which is placed 18 in. from the lens? What focal length lens must be used?

CHAPTER 19

LIGHT—OPTICAL INSTRUMENTS

Vocabulary

Anastigmat, a lens combination which is corrected for astigmatism.
Annular (*annulus,* a ring), ring-shaped.
Diaphragm, an annular disc used to keep rays of light from passing through the edges of a lens.
Meniscus, crescent-shaped.
Photo-electric, a tube in which light waves of varying intensity will cause a variation of the electric current.

411. Optical Instruments. The eye itself is one of the most used optical instruments. Often lenses are used to correct some defect in the eye. For reflectors in headlights, and for use in house lighting, mirrors are of great importance. In the majority of optical instruments, a lens or a combination of lenses is used to form images. Such instruments may be used to magnify an object, to make a distant object seem nearer, to project an image on a screen, or to distribute light properly. In the diagrams, we shall use a single lens instead of a combination of lenses in order to secure simplicity. For the sake of simplicity, only the secondary axes will be used in many of these diagrams to show how the lens forms images.

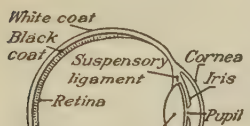


FIG. 472. — Structure of the eye.

412. The Eye. In many respects the eye is the most perfect optical instrument. The structure of the eye is shown in Fig. 472. 1. The white outer coat of the eye is tough and hard; hence it preserves the shape of the eye-ball and also serves to protect the eye. 2. The middle coat of the eye is

black. It is interesting to note that the interior of nearly all optical instruments is blackened to absorb stray light waves that might be reflected from the walls and blur the image. 3. The inner coat, called the *retina*, covers the

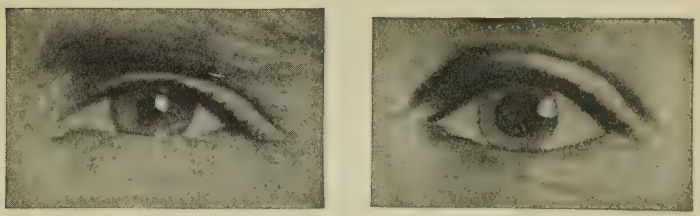


Fig. 473. — At left, pupil in strong light is contracted. At right, pupil in subdued light is expanded.

back part of the eye-ball only. On the retina, the nerves of the eye are spread out, thus forming a sensitive screen for the reception of the image. 4. The *crystalline lens* is used to form a real image upon the retina. 5. The iris serves as a diaphragm to cut off the rays of light from the edge of the lens. The opening in the iris is called the *pupil*. In a dark room the pupil becomes enlarged to admit more light, but in bright sunshine the pupil is reduced until it is about the size of a pin-head. (See Fig. 473.)

413. How the Eye Forms Images. The image formed on the retina by the crystalline lens is real, inverted, and smaller than the object. (See Fig. 474.) The eye can form an image of an entire house a hundred feet away. Hence the image must be reduced decidedly. The image is bright and well-defined or clear-cut. If an object is brought nearer the eye, the muscles that support the lens contract and change the shape of the lens. Thus they shorten the focal length and

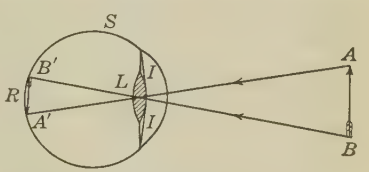


Fig. 474. — Image formed by eye.

make it possible for the eye to form an image of near objects. The eye is said to be self-focusing, or to have the *power of accommodation*. In the normal eye the lens can be made convex enough to see clearly objects as close as 10 in., or 25 cm. This distance is called the nearest distance for distinct vision. When we read for a long time with the book at this distance, the muscle which keeps the lens properly focused becomes tired. When the muscle relaxes, the lens becomes flatter and more distant objects are in focus. Looking at a landscape after one has been reading for some time rests the eyes.

414. Defects of the Eye. We have seen that the normal eye is "self-focusing," since the muscles in the eye can change the shape of the crystalline lens enough to make the image fall upon the retina, whether the object is near by or quite remote. Some persons are *near-sighted*. Either the eye-ball is too elongated, or the lens is so convex that the image is formed in front of the retina. Only when the object is brought very close to the eye, so that its rays are diverging when they reach the lens, will such an eye give distinct vision. (See Fig. 475.) The remedy for *near-sightedness* consists in wearing glasses which partially neutralize the convexity of the lens. Glasses with concave lenses are used, since they make the rays of light more divergent. Many children who are slightly near-sighted are apt to have normal eyes when they reach maturity.

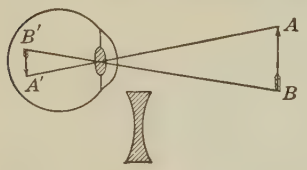


FIG. 475.—Near-sightedness remedied by concave glasses.

If the eye-ball is too short, or the lens is too flat, *far-sightedness* will result. The lens cannot form the image on the retina, unless the object is held at a considerable distance. One often sees a middle-aged person holding a paper at arm's length when reading. The lens in his eye has lost some of the power of accommodation. (See Fig. 476.) Far-

sightedness may be remedied by wearing glasses with convex lenses. Glasses with double lenses, bi-focals, are sometimes used to enable a person to see near objects with one set of lenses, and to see more remote objects with the other set. Frequently the upper part of the lens is cut away. Such glasses enable the wearer to see near-by objects. For more remote objects glasses are unnecessary, since the person sees clearly at a distance.

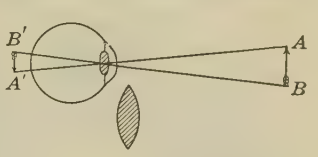


FIG. 476. — Far-sightedness remedied by convex glasses.

Sometimes either the cornea does not have a perfectly curved surface, or the surface of the lens itself may not be regular. In such cases all parts of an object are not in focus at the same time. To such an eye the lines in Fig. 477 do not all appear equally distinct at one time. Some of them are in focus, but the others form a blurred image. For cases of *astigmatism*, glasses having lenses especially ground to counteract these irregularities are used.

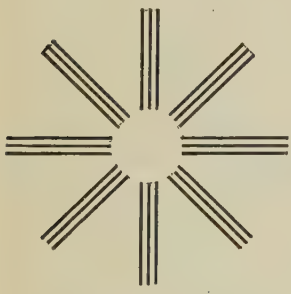


FIG. 477. — Astigmatism.

415. Flat and Meniscus Lenses. The lenses *A* and *B* of Figs. 459 and 460 are *flat lenses*. When such lenses are used in eye-glasses, the wearer must look through the center of the lens to have a distinct image formed. Thus he is forced to turn his head from side to side, or up and down, in order to see different parts of a stationary object or to see clearly a moving object. The small center calendar of Fig. 478 is in focus with such a lens, but the others cannot be distinguished. There is another objection to the use of flat lenses. The center of the lens, as shown in Fig. 479, is nearer the eye than the edges. Such a lens must be set farther from the eye than the

meniscus lens shown in the same figure, or the eye-lashes will brush against the center and cause annoyance. The lenses *C* in Figs. 459 and 460 are both meniscus lenses. With lenses of this type, the wearer of eye-glasses has a fairly wide range of vision without the necessity of turning his head to see clearly. Fig. 480 shows the effect of meniscus lenses.

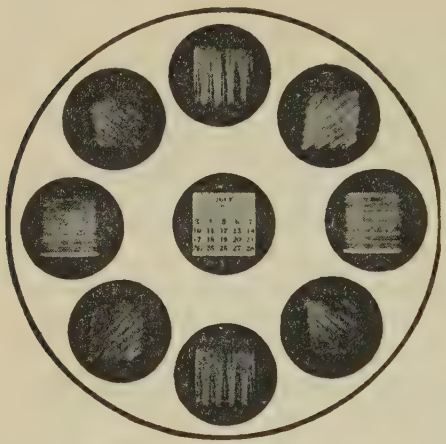


FIG. 478. — Effect of flat lenses.

416. Apparent Size of an Object. We all know that a man at a distance of a quarter of a mile appears so small that one may mistake him for a boy. A half dollar held an arm's length distant seems as large as the sun at its distance of over 92,000,000 miles. If we study Fig. 481, we see that the image of AB that is formed on the retina is larger than the image formed by $A'B'$. Both have the same length, but $A'B'$ is twice as far away. The *visual angle* ACB is larger than the angle $A'CB'$. Hence AB appears larger than $A'B'$. When one knows the distance, he can estimate the size of an object. Much experience is needed before a person can estimate size and distance. A baby reaches for the moon and cries because he cannot get it. Later he learns to estimate distance by means of intervening objects. When the moon is rising or setting, intervening objects enable him to judge more accurately its size and distance.

FIG. 479. — Flat and meniscus lenses.

417. Estimating Distances. In the preceding section we learned that one may judge distances, provided he knows the size of the object. He forms an estimate from the size of the visual angle. Such a method is not very accurate, and it is reliable for short distances only. If we close one eye and try to stick a pin in the center of a letter *O* on a printed page held at arm's length, we find that the size of the image or the visual angle will not enable us to judge distance accurately. Most persons miss the center by a quarter of an inch or more. When the experiment is repeated with both eyes open, nearly everyone can hit the center almost exactly. If the teacher stands near the blackboard with his arm extended, a pupil directly in front of him, but in the back part of the room, cannot judge the teacher's distance from the blackboard, provided the pupil keeps one eye closed. With both eyes open, he can judge quite accurately. These experiments show us the importance of *binocular vision.* With our right eye we see a little more of the right side of an object and with our left eye a little more of the other side. Thus we have perspective.

FIG. 480. — Effect of meniscus lenses.

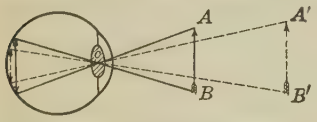


FIG. 481. — Size of object.

If we refer to Fig. 482 we see that the eyes are rolled inward to some extent when we focus both of them upon the

point *D*. A certain amount of muscular effort is used in such a case. By experience we learn to estimate the distance *CD* by the angles *CAD* and *CBD*. We use the distance between our eyes as a base line, and learn to estimate distance by the amount of muscular effort required to roll the eyes inward until both are focused upon the object. The nearer the object, the smaller these angles become, and the more effort is required.

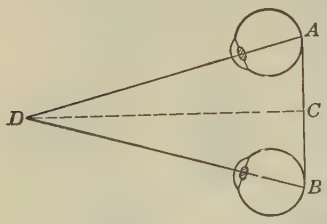


FIG. 482. — Judgment of distance.

Battleships find the range at sea by using for the base line a tube 12 to 15 ft. long. At each end of the tube there is a total reflecting prism. These prisms are focused upon the distant object, and the angles they make with the base line are carefully measured. Then the distance, which corresponds to the altitude of the triangle, is computed by trigonometry. Such *range-finders* are generally calibrated to read distances directly.

418. The Camera. The pin-hole camera, § 380, or the camera obscura, is said to have been invented by Roger Bacon. It was described in the early part of the sixteenth century by Leonardo da Vinci when he told how images of outside objects are formed in darkened rooms by a small circular hole in the shutter. About the middle of the same century Cardan improved the camera obscura by placing a double convex lens in the opening.

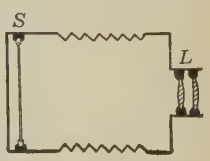


FIG. 483. — Diagram of camera.

If we compare Fig. 483 with the diagram of the eye, we find that the photographic camera is modeled after the eye. The sensitive screen *S* corresponds to the retina and receives the image. The lens or combination of lenses acts like the crystalline lens of the eye. It forms upon

the sensitive plate a real, inverted image, smaller than the object. The diaphragm, or stop, regulates the amount of light that enters the camera just as the iris permits the proper amount of light to enter the eye through the pupil. The shutter excludes light just as the eyelids do. The interior of the camera is blackened to absorb stray rays of light.

419. Eye versus Camera. In several ways the eye is decidedly superior to the camera. The eye is self-focusing, while in the camera the lens must be moved nearer to the sensitive plate or farther away, depending entirely upon the distance of the object. For this reason the side walls of the camera are collapsible. The iris automatically regulates the amount of light the eye needs for forming clear images. The operator needs considerable experience to adjust the diaphragm of a camera properly for different light intensities. With the eye we get distance and perspective; the photograph formed by the camera does not have perspective.

On the other hand, the camera has some advantages over the eye. It gives us a picture of all the details of the object, while some of the details of an image formed on the retina are so feebly impressed that they are either ignored or quickly forgotten. The photograph gives us a picture of an object at a certain instant in a given position, while the image received through the eye may be a *composite* picture of several successive images in different positions. Each image persists for about $\frac{1}{16}$ second before another that is distinct from the first may be formed. Thus we remember a composite picture, possibly formed by blending several images. For this reason, two truthful persons may be almost contradictory in describing an accident both have witnessed. In one of the Olympic games the judges awarded a runner fifth place. The motion pictures later showed unquestionably that he finished in second place. Motion pictures of football games show the coach clearly what each player did during the game.

420. Optical Illusions and Camouflage. The expression "You cannot fool me, I saw it" is so common that one might infer that the eye is infallible. Yet we pay a magician to fool the eye. Often the image which the eye forms is influenced by former experiences which we have had. When our judgment based upon such experiences is at fault, then optical illusions occur. (See Fig. 484.) Do the lines appear to be parallel? There are many similar illusions of direction. (See Figs. 485 and 486.) A brown log or stump in the darkening twilight may appear to the observer as a dog or other animal when our imagination modifies the image on the retina.

FIG. 484. — Optical illusions.

Many insects are very hard to see when at rest on twigs or leaves because they assume the same color as their surroundings. This protective coloration is common among animals that change a brown or tawny coat of summer for one of white in winter. Many fishes change their colors and take the color of their surroundings. The white stripes and patches of the tiger, zebra, and giraffe resemble spots or streaks of sunlight passing through foliage or reflected by leaves.

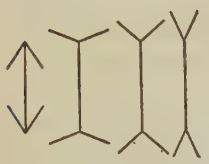


FIG. 485.— Which line is longest?

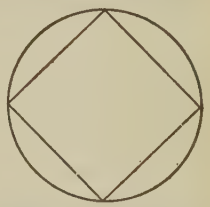


FIG. 486.—The circle appears flattened at the corners of the squares.

The art of mimicry and protective resemblance was much practiced during the World War. Battleships were painted gray to produce low visibility. They blended with the horizon colors and were hard to see. Paint was much used to give an object the appearance of its surroundings. Fig. 487

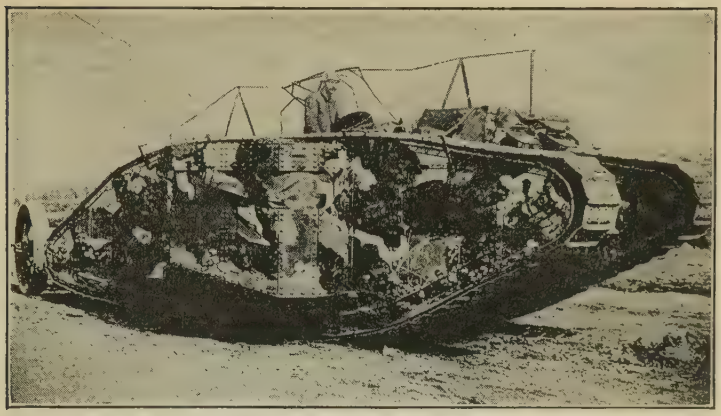


FIG. 487. — Camouflaged tank. Hold picture at distance of 4 ft. and notice loss of detail.

shows a tank that was covered with "dazzle paint" to change its appearance. By similar methods of *camouflage* many ships escaped the enemy submarines.

421. Anastigmat and Rectilinear Lenses. When ordinary lenses are used with the diaphragm well opened, the image produced is generally sharp and well defined at the center, but it is "streaky" or blurred near the edges. This defect of lenses is known as astigmatism. By using a combination of lenses of suitable refractive indices and focal lengths, like that shown in Fig. 488, it is possible to make an *anastigmat* lens which gives good definition over a wide area. At the same time the lens combination must be corrected for spherical and chromatic aberration. (See section 445.)

FIG. 488. — Anastigmat lenses.

Lenses that can be used with a large aperture are fast,

and they can be used for high-speed work. The *effective aperture* of a lens is equal to the diameter of the lens as it appears when seen through the front lens. The speed of a lens depends upon the ratio of its effective aperture to its focal length, or upon its *relative aperture.* In an *F*-4 lens, the focal length is 4 times the effective aperture. Such a lens is 4 times as fast as an *F*-8 lens, and 16 times as fast as an *F*-16 lens. The speed ratios are proportional to the squares of the relative apertures.

If a plano-convex lens is placed in a camera so the flat side is toward the object, the image that is formed is distorted so that a square has the appearance shown by the solid lines of Fig. 489*A*. When the lens is turned so its convex side faces the object, the opposite effect is produced. (See Fig. 489*B*.) Distortion is produced by all single lenses, the effect being especially noticeable in pictures of buildings with straight lines. The defect may be remedied by using two lenses with their corresponding curves facing in opposite directions and with the diaphragm between the lenses. Such a combination is called a *rectilinear* (straight-line) lens.

Fig. 489. — Effect of diaphragm upon straight lines.

422. The Simple Magnifier. Everyone has used a simple magnifier to produce an enlarged image of an object that is near the eye. We have learned that the *apparent* size of an object increases as it is brought nearer to the eye, because the visual angle is enlarged. We found, too, that the eye does not form a clear image of an object that is brought nearer the eye than 10 in., or 25 cm. Since the muscles of the eye cannot make the lens more convex, we may use a convex lens to assist the eye in forming clear images of objects closer than 10 inches.

A double convex lens of rather short focal length is generally used as a simple magnifier. This lens is held a little

nearer to the object than its focal length and the eye is placed close to the lens. This is a practical example of Case 6, and the image formed is enlarged, virtual, and erect. To represent the magnifier graphically we merely draw a diagram to show how an image is formed when the object is nearer the lens than its principal focus, and place the eye on the opposite side near the lens. (See Fig. 490.) Since the object is very near the principal focus, the *approximate* magnifying power of a simple magnifier equals

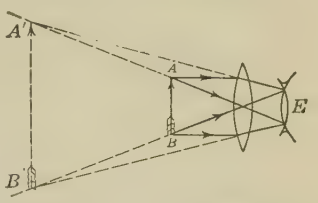


FIG. 490. — Simple magnifier.

$$\frac{\text{the least distance for distinct vision}}{\text{focal length of the lens}}.$$

Thus we divide 25 cm. by the focal length in cm., or 10 in. by the focal length in inches. A lens of 5 cm. focal length will magnify about 5 diameters.

423. The Compound Microscope. The invention of the compound microscope by Janssen marked the beginning of a new era in the study of plant and animal physiology. Without the microscope, nothing would now be known concerning the action of bacteria in producing diseases. By its use, Louis Pasteur learned why foods spoil and how certain diseases are caused. If it were not for the serums and antitoxins which his work made possible, at least one in eight of our readers would have died in infancy.

From our study of lenses, it seems as if we ought to be able to form an enlarged image by means of one lens and then magnify this image by the use of another lens. That is exactly what the *compound* microscope does. Since the image to be magnified must be a *real* image, we make use of Case 4 to form the first image, and of Case 6 to magnify

this image. The two convex lenses are mounted at opposite ends of a brass tube whose length is adjustable.

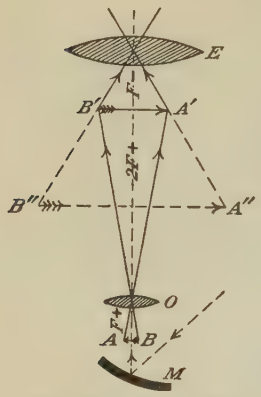


FIG. 491. — Compound microscope.

In Fig. 491 we use a converging lens as the objective O, and the object AB is placed a trifle farther from the lens than its focal length. At $A'B'$, a distance slightly more than twice the focal length of the lens, we have formed an enlarged, real, inverted image. This image is enlarged by the eye-piece E which acts as a simple magnifier. The mirror M is used to reflect strong light upon the object. Since the light is spread out over a greater surface when we form an enlarged image, such an image will become fainter and fainter as we increase its magnification.

The magnifying power of the objective is approximately equal to the length of the tube L, divided by the focal length F of the objective, or $\frac{L}{F}$. The magnifying power of the eye-piece equals $\frac{25}{f}$ (cm.). The total magnification is equal to the product of the two, or $\frac{25L}{fF}$.

Suppose the tube of a microscope is 16 cm. long, the focal length of the objective is 0.5 cm., and the focal length of the eye-piece is 2.5 cm. The objective magnifies the object 32 diameters, and the eye-piece magnifies it 10 diameters. The total magnification is 320 diameters.

424. The Telescope. In the *refracting telescope*, the eye-piece E magnifies the real image, which is produced by the objective O. (See Fig. 492.) The telescope differs from the

microscope in this respect. The objective of the microscope produces an enlarged image of an object distant more than *once* the focal length, but the objective of the telescope produces a real image, reduced in size but exceedingly bright, of an object distant much more than *twice* the focal length of the objective. The objective is made very large so that it may collect a large quantity of light rays to make the image very bright.

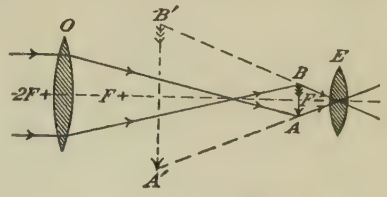


Fig. 492. — Refracting telescope.

The objective of the Yerkes *astronomical* telescope has a diameter of 40 in. and a focal length of more than 60 ft. Such an objective forms a real image of distant heavenly bodies, which is so bright that it can be highly magnified by the eye-piece. When an eye-piece whose focal length is 0.25 in. is used, this telescope magnifies almost 3000 diameters. The magnifying power is approximately equal to the focal length F of the objective divided by the focal length f of the eye-piece, or $\frac{F}{f}$. (See Fig. 493.)

In the *reflecting telescope* a large concave mirror is used instead of a lens to collect the light rays and form the real image, which is then magnified by the eye-piece. With astronomical telescopes and with microscopes, the image is always inverted and reversed, but that matters little to the observer; it does make a decided difference, however, when one uses a telescope to see distant objects on the earth's surface.

In the *terrestrial telescope* the objective and the eye-piece form images in just the same manner that they do in the astronomical telescope. Another lens L is used to reinvert the image so we may see it erect. Such a lens is placed just twice its focal length from the real image formed by the

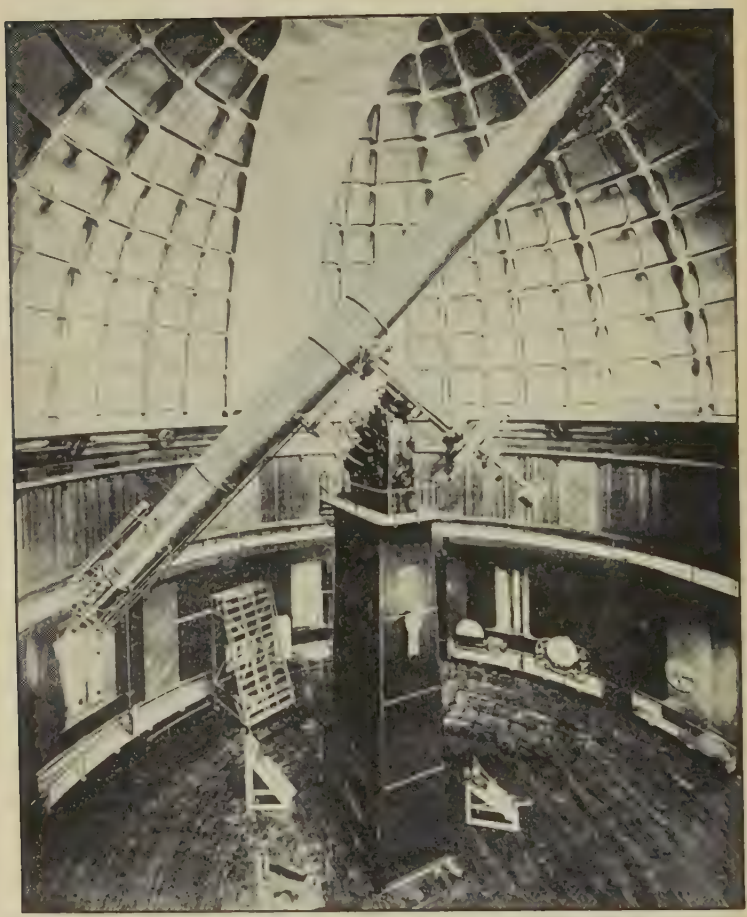


FIG. 493. — The Yerkes telescope and observatory. The telescope and counterpoises (21 tons) are moved by electric motors and controlled by a clock, which keeps the tube pointed at any astronomical body. The floor may be raised or lowered to meet the needs of the observer.

objective. At twice its focal length, it forms an image on its opposite side; this image is then magnified by the eye-piece. (See Fig. 494.)

Telescopic sights are sometimes used on long range rifles. Cross-threads intersecting at right angles, are suspended in the telescope. When the telescope is adjusted so the image is focused on the intersection of these threads, then the object, the center of the objective, and the point of intersection are all in the same straight line. Surveyors use the same kind of a telescope in their transit instruments and levels.

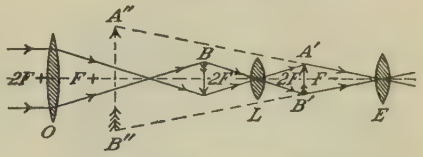


FIG. 494. — Terrestrial telescope.

425. Opera Glasses. The opera glass is lighter than the telescope, and, having two tubes, it has the advantage of giving binocular vision.

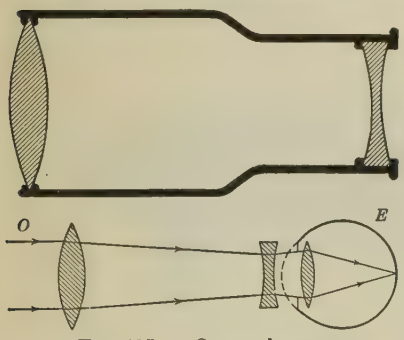


FIG. 495. — Opera glasses.

The eye-piece has the same focal length as the crystalline lens of the eye, but it is concave; hence it practically neutralizes the lens of the eye. The objective, a lens of larger size and greater focal length, is then virtually substituted for the crystalline lens. Opera glasses usually magnify only 3 or 4 times, the magnifying power being approximately equal to the length of the tube in inches. The image *appears* erect, since it is formed on the retina the same as images formed by the lens of the eye.

In Fig. 495, *E* is the eye-piece, and *O* is the objective. Some binoculars are made with total reflecting prisms, like

those shown in Fig. 496. The lenses are set farther apart and the visual angle is increased; hence the observer can scan a wider field without changing his position.

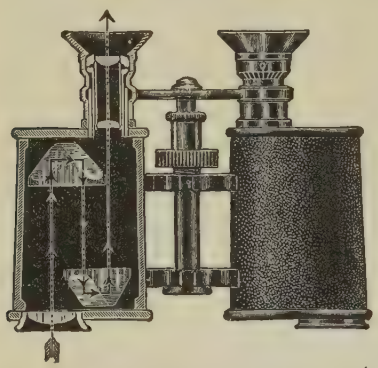


Fig. 496. — Binoculars. Total reflecting prisms.

426. The Optical Lantern. Everyone is familiar with the lantern, Fig. 497, which is used to throw an enlarged image of a transparent slide upon a screen. The objective *O*, Fig. 498, consists of a combination of converging lenses which act as a single lens. The slide *S* is placed just a little farther from the lens than the principal focus. The screen is distant more than twice the focal length. (Case 4.) The image is real, enlarged, and

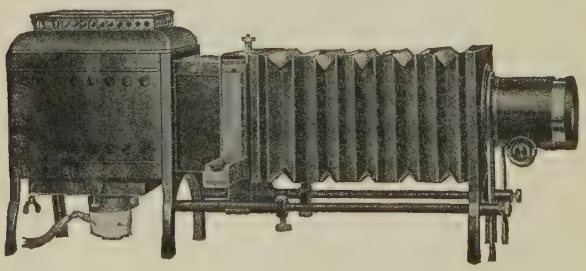


Fig. 497. — Optical lantern.

inverted. The slide is inverted so that the image will appear upon the screen in an erect position.

Since the image is enlarged so much, a very high candle power lamp *L* must be used to illuminate the slide. At one time the arc lamp was largely used, but now an incandescent lamp of great intensity is more common. A concave mirror

is placed behind the lamp to focus more rays upon the slide, and two large diameter plano-convex lenses called condensers, C and C', are placed about focal length in front of the lamp for the same purpose.

427. Motion Pictures. The projector used to throw motion pictures upon a screen does not differ in principle from the optical lantern. The image is formed by an objective in the same manner, and condensers are used to concentrate a large quantity of light upon a strip of film which takes the place of the slide. The mechanism is more complex. A roll of film is unwound from one reel or spool and wound upon

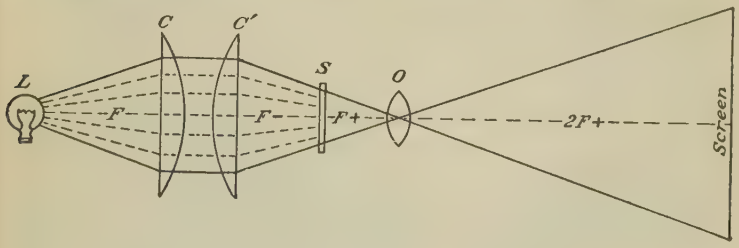


Fig. 498. — Optical lantern.

another. Each picture must come to a complete stop while it is being shown. Then it moves on and another is substituted for it. A revolving shutter covers the picture while the film is in motion. (See Fig. 499.)

The principle known as the *duration of vision* is utilized in showing motion pictures. The image formed upon the retina persists from $\frac{1}{20}$ to $\frac{1}{10}$ of a second after the object is removed. If a second object is introduced before that time has elapsed, a continuous effect is produced. The spokes of a rapidly rotating carriage wheel succeed one another so fast that the wheel appears solid. Before the image of one spoke fades, another is formed. In preparing a film, from 16 to 50 pictures of a moving object are taken per second. When thrown upon a screen, the pictures succeed one

another at about the same rate, thus giving a continuous effect.

If we examine the strip of film shown on the opposite page (Fig. 500), we find that each picture is slightly different from the preceding one. When film is made from nitro-cellulose, it

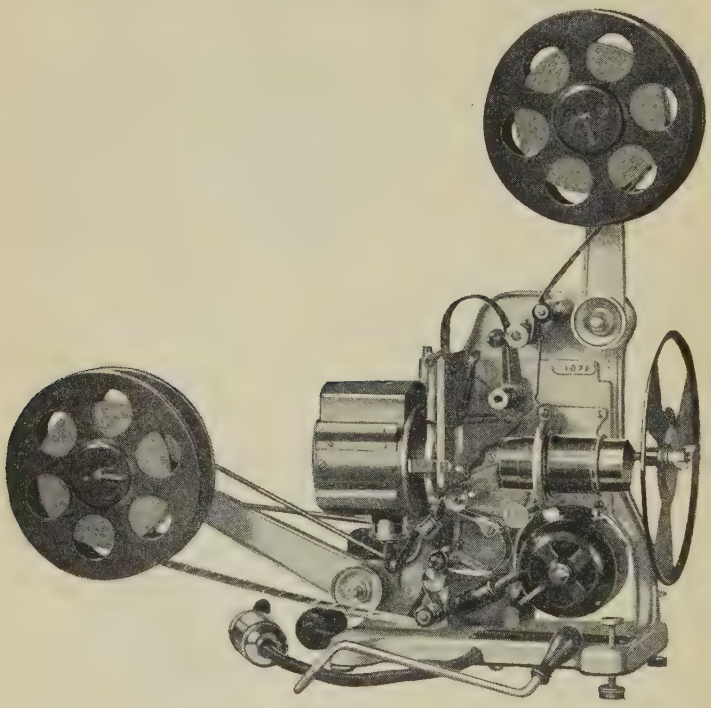


Fig. 499. — Safety standard motion picture projector.

is so inflammable that the motion picture machine and film must be enclosed in a fire-proof booth. A so-called safety film is made of cellulose acetate, which is not so highly inflammable. In many states such film may be used without being enclosed in a fire-proof compartment.

Certain optical illusions are common in viewing motion

pictures. The propeller of an airplane just as the engine is being started appears to be turning backward. The successive appearances of the propeller blades are slower than the succession of pictures on the screen. Occasionally we see on the same film some automobiles in which the wheels appear to turn backward, others in which the wheels appear to be turning in the proper direction, and still others in which the wheels appear to be standing still as the car moves. These conditions depend upon the speed at which the spokes succeed one another as compared with the rate at which successive pictures are shown on the screen.

428. Talking Motion Pictures. In order to have talking motion pictures, it is necessary to record the sound waves upon the film so the timing will be perfect. In the *vitaphone* this is accomplished: 1. By the use of a microphone which changes the sound waves into electrical variations; 2. The electrical variations are amplified and then used to vary the intensity of a narrow beam of light; 3. As this narrow beam of light is focused upon the film through a narrow slit, it produces light and dark bands that correspond to the pitch of the sound produced. Fig. 501 shows the sound waves on a separate film, and Fig. 502 shows how they are recorded on the margin of the picture

film. Thus the timing is perfect, and if the film breaks, the sound stops at the same time the picture is interrupted.

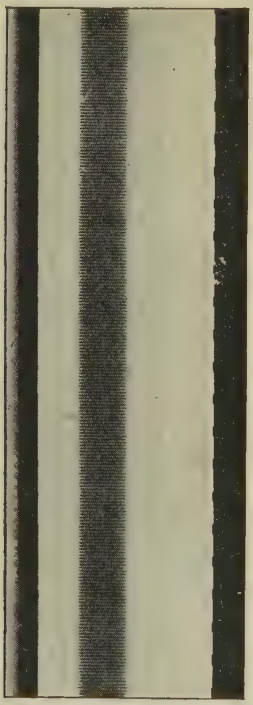


FIG. 501. — Sound film. (*Courtesy of Bell Telephone Laboratories.*)

FIG. 502. — Sound film on margin of picture film. (*Courtesy of Bell Telephone Laboratories.*)

Fig. 503 shows the device or mechanism used for recording sound on the film.

When such a film is shown, a light is focused upon the sound film. Of course its intensity is varied as it passes through the film. These light variations are picked up by a photo-electric cell (electrical eye), which converts them into

electrical fluctuations. After amplification, the electrical waves are carried to a loud speaker.

In making the *movietone* pictures, a special recording Aeo light is inserted in the back of the camera so the light will fall with varying intensities upon the margin of the picture film at the same time the film is exposed. These light variations are caused by amplified electrical fluctuations

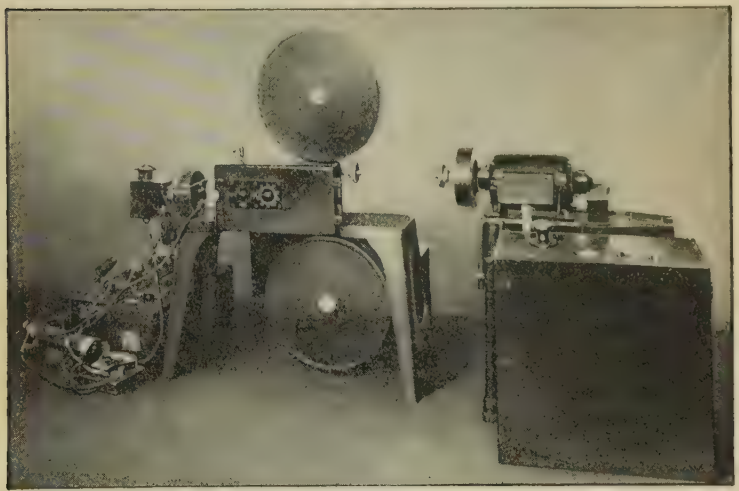


FIG. 503. — Mechanism for recording sound on film. (*Courtesy of Bell Telephone Laboratories.*)

produced by means of a microphone. In falling upon the film, the light waves pass through a slit on a special quartz plate, which is silvered on one side. The silver coating is scratched away to make a slit 0.00008 in. wide and only 0.01 in. long. Thus the light waves trace the sound record on the *margin* of the film. These films are reproduced in the same manner as the vitaphone films.

429. Lampshades and Illumination. Daylight is usually well diffused, but for the proper distribution of artificial light, shades or reflectors are essential. In a library or reading

room the light should be fairly close and concentrated. For living rooms and assembly halls, the illumination is more general.

In the *direct* system of illumination, the light shines directly upon the object to be lighted; a rather narrow shade or a concave reflector may be used to concentrate more light upon the object. This is the most economical system of lighting, but the eyes are sometimes injured by the glare which comes from the light itself or from the reflector. In electric lighting, the bulbs are either frosted or made of translucent glass in order to modify the glaring light of the filament. (See Fig. 504.)

Fig. 504. — Direct lighting.

For general illumination the *indirect* or the *semi-indirect* system is often used. With the indirect system the lamps are placed near the ceiling; a large, opaque, bowl-shaped reflector placed beneath the lamp reflects the light to the ceiling, whence it is diffused to all parts of the room. (See Fig. 505.) If the ceilings are white, an even diffusion of the light is thus secured and the system is fairly efficient. White or light yellow walls and ceilings may reflect as much as 50% of the light they receive. Red, brown, or green walls absorb about 85 or 90% of the light received, and reflect only 10 to 15%; hence they are not suitable for indirect lighting. While the indirect system of lighting is always more costly, yet the light is soft and pleasing and sharp shadows are eliminated.

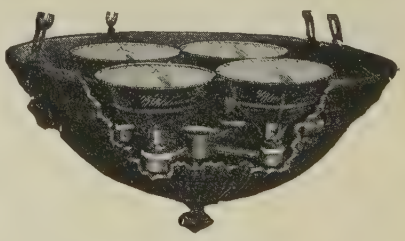


Fig. 505. — Indirect lighting.

In the semi-indirect system of lighting, the lamp is partially enclosed in a translucent globe. (See Fig. 506.) A part of the light is thus reflected to the ceiling and the remainder is diffused directly through the globe. This system is designed

FIG. 506. — Semi-indirect lighting.

FIG. 507. — Diffusion lighting.

to combine the advantages of the direct and the indirect systems. Fig. 507 shows a method of *diffusion* lighting now in common use.

Much progress has been made within the last few years in the field of illuminating engineering. The practice of outlining the domes and towers of prominent buildings, or even the buildings themselves, with rows of incandescent lamps has in certain cases been superseded by *flood lighting*. Fig. 508 shows the Woolworth Building at night. The tower is beautifully lighted by a battery of projectors. A single projector used for this type of lighting is shown in Fig. 509. The battery of projectors, Fig. 510, may be used for lighting towers or buildings, or it may find use in lighting construction jobs where night work is necessary.

FIG. 508. — The tower of the Woolworth Building lighted by a battery of projectors. Flood lighting.

For advertising purposes neon tubes are being extensively used. A glass tube may be bent into any desired shape to form letters or designs. The tube is then exhausted and filled with neon gas under low pressure. Electrodes are sealed in the ends of the tube for making connections with an electrical circuit. When the current is turned on, the whole tube is filled with a yellowish orange light. Other colors can also be produced. Such tubes are popular because they are beautiful and striking, and the consumption of current is very low. (See Fig. 511.)

Fig. 509. — Projector for flood lighting.

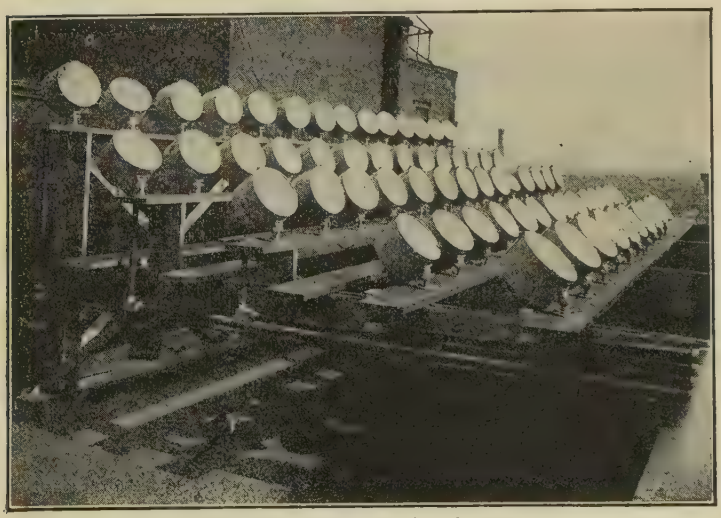


Fig. 510. — Battery of projectors.

FIG. 511. — Making neon tubes for advertising signs.

QUESTIONS

1. Why is the image formed by a compound microscope inverted?

2. Why is the interior of optical instruments painted black?

3. In old age the lens of the eye loses the power of accommodation. What kind of glasses is used by old persons as reading glasses?

4. Convexo-concave or concavo-convex lenses (meniscus) are now more often used in spectacles than the flat lenses. What advantages do such meniscus lenses have?

5. Where is the slide placed in an optical lantern with respect to the focal length of the objective?

6. What advantages has the eye over the camera as an optical instrument? What are its disadvantages?

7. Why does the moon appear larger when near the horizon than when it is on the meridian?

8. Prism glass like that shown in Fig. 512 is often used instead of ordinary window glass. What advantage has it? What are its disadvantages?

9. How is it that owls and cats can see so well at night? What shape has the pupil of a cat's eye when seen at night? When observed in daylight?

10. Name several optical instruments you have used that form real images. Name several that form virtual images.

11. Why do the parallel rails of a railroad track appear to meet at a distance?

12. Draw a diagram to show where a light must be placed with reference to a large double convex lens to produce a spotlight? Where is the light placed with reference to the lens in a lighthouse?

13. In what respects is a photograph of an accident better than the testimony of an eye-witness? In what ways is the testimony superior?

FIG. 512. — Prism glass.

14. The State of Massachusetts does not issue a car license until the headlights have been properly adjusted. How would you proceed to adjust headlights? (See manual issued with any car.)

15. What is meant by binocular vision? What are its advantages?

PROBLEMS

1. A lead pencil 6 in. long when held 12 in. from the eye appears as tall as a tree 100 ft. away. How high is the tree?

2. A reading glass has a focal length of 5 in. What is its magnifying power?

3. The tube of a microscope is 180 mm. long. What is its magnifying power when the eye-piece has a focal length of 2 cm., and the objective has a focal length of 3 mm.?

4. A camera has a lens whose focal length is 6 in. If the plate is 6.25 in. from the lens when the camera is in focus, how far away is the object? Suppose the object is 6 ft. high by 8 ft. wide, what is the smallest sized plate that can be used to show all of the object at the distance found?

5. If a film is one and one-eighth inches wide, what are the relative distances of the screen and the film from the lens, if the image just fills a screen 9 ft. wide? If a theater is 64 ft. long, what is the actual distance between lens and film when the picture is in focus? Calculate the focal length of the lens that will be needed.

6. A picture 8 ft. high by 12 ft. long hangs on one wall of a room. A photographer, who wishes to take a photograph of this picture, places a camera which has a focal length of 12 in. just 13 ft. from the picture. How far from the lens will the image be formed? What size plate must the photographer use to include the entire picture?

7. The lens combination of a compound microscope magnifies an object 800 diameters. How many times as large does the cross-sectional area appear as the object which is being examined?

8. A photograph is being taken of a building which is just 100 ft. distant. The plate upon which the exposure is being made is exactly 1 ft. from the lens. Calculate the focal length of the lens. If the picture just covers a plate that is 6 in. high by 8 in. long, what is the height and length of the building?

CHAPTER 20

LIGHT—COLOR

Vocabulary

Analysis, taking apart, or decomposing.
Synthesis, putting together, or combining.
Achromatic, without color.
Polychromatic, composed of many colors.
Polarized, light given a definite direction, or vibrating in one plane only.

430. Dispersion or Analysis of Light. Cut-glass dishes and pendants from candlesticks and chandeliers give a beautiful display of colors when the sun shines upon them. If we pass a beam of sunlight through a glass prism and let the rays fall upon a white screen, a band of seven colors may be seen. Such a band of colors is called a *solar spectrum.* This experiment shows that sunlight is complex and it may be separated into several colors; it is *polychromatic.* Light that is made up of a single color is said to be *monochromatic.*

Fig. 513 shows the order in which the seven colors of which sunlight is composed appear on the screen. The *dispersion* of light is due to the fact that some colors are refracted more than others as they pass through the glass prism. The violet light is refracted more than the other colors, since it has the shortest wave length. The red rays are bent least in passing through the prism. The rainbow, which will be more fully explained later, is a beautiful example of a solar spectrum formed by the dispersal of sunlight colors.

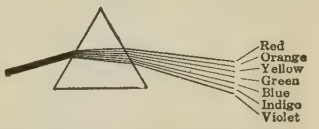


Fig. 513. — Dispersion of light.

431. Color. In sound we studied the *chromatic* (colored) scale and learned that pitch depends upon the number of vibrations that reach the ear per second. *Color bears the same relation to light that pitch does to sound.* It depends upon the number of vibrations that reach the eye per second. If we hold one end of an iron poker in a fire, the electrically charged particles in its atoms oscillate faster and faster as the temperature rises. Eventually the vibration becomes rapid enough to give out waves to which the eye is sensitive. The first color that the eye can detect is a very dark red. The dark red color is produced by waves that are 0.00081 mm. in length. Longer waves than this affect our temperature sense or our wireless receiving set, but they cannot be perceived by the eye. If we continue to heat the poker, it will give off orange waves, and then yellow. Finally it becomes white hot. If we pass its light through a prism, it will be separated into the seven colors produced by a solar spectrum. The shortest waves which the eye can perceive are those which produce violet light. They are only 0.00039 mm. in length. Shorter waves are known, those which produce the X-rays and certain chemical effects, but the eye is not sensitive to them. The following table shows the wave length of the different colors:

Very dark red	0.00081 mm.	Green	0.00052 mm
Red	0.00065 mm.	Bluish green	0.00050 mm.
Reddish orange	0.00064 mm.	Blue	0.00047 mm.
Orange	0.00060 mm.	Indigo	0.00043 mm.
Yellow	0.00058 mm.	Violet	0.00041 mm.
		Extreme limit of visibility	0.00039 mm.

The table shows that the range of frequencies to which the eye is sensitive is only about one octave. Of course the formula, $v = nl$, applies to light waves as well as to sound waves. The velocity of light is about 300,000 kilometers per second, or 300,000,000,000 mm. per second. If we divide this number by the wave length of violet, 0.00041 mm, we

find that a particle must vibrate over 730 trillion times per second to produce violet light.

432. Color of Objects. It is always difficult for students to think of color as a property of light waves rather than of objects. We are accustomed to say that a dress is blue or red, but if we put a piece of blue cloth in the red portion of a solar spectrum in a darkened room, it seems to be black. If we put a piece of red cloth in the blue portion of a solar spectrum, it will also appear black. *If an object absorbs all the rays of light it receives, it is called black. An object that reflects all the light it receives is said to be white.* We say that *an opaque object is blue if it reflects blue light and absorbs all the other colors.* If we hold a piece of blue paper in the red portion of a spectrum, it cannot reflect any light, because no blue light falls upon it; it is capable of reflecting blue only.

Artificial lights are apt to be deficient in certain colors, especially the blue and the violet. Hence a piece of ribbon that is blue in sunlight is apt to appear green by candle light. The mercury vapor lamp, which is much used by photographers, is deficient in red and yellow rays. A person sitting under such a light appears pale and ghastly.

From these observations, it seems clear that the color of an opaque object depends: (1) upon the kind of light it receives; (2) upon its ability to reflect light. Strictly speaking, color is a property of light waves that depends entirely upon their wave length.

The color of transparent objects depends upon the color of the light waves they transmit. Ordinary window glass transmits all the colors and is colorless. Red glass absorbs all the colors except the red, which it transmits.

433. Synthesis of Colors. Since we can separate or analyze compound light, it might be expected that the process could be reversed and simple colors combined to form compound light. This can be done in two ways: 1. If we place

a second prism, arranged as in Fig. 514, in the solar spectrum formed by a prism, the colors will recombine and produce white light. Other complex colors can be built up in a similar way by synthesis. 2. If we rotate rapidly a disc colored as marked in Fig. 515, the colors will combine to produce white light. The light from one color forms an image on the retina which persists until the other colors have been reflected to the eye in turn. In this manner we see all of them at one time, and they blend to form white light, provided pure spectral colors are used. Since the colors fade to some extent, pure white is seldom seen when this experiment is performed.

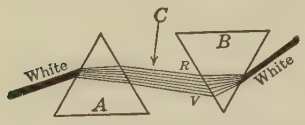


FIG. 514. — Synthesis of light.

434. Complementary Colors. Suppose we repeat the first experiment performed in the synthesis of light. If we shove an opaque cardboard into the spectrum of Fig. 514 at *C* just far enough to cut off the red rays, the other six colors will combine as they pass through the second prism and produce green light. If we subtract red light from white light, we have green light left; hence it is to be expected that we could combine red light and green to form white light. This can be done by using a rotating disc, with the colors green and red, in the manner described in § 433. *Any two colors that combine to produce white light are said to be complementary.* If the blue rays of a solar spectrum are intercepted, the other six colors unite to form yellow light. Hence blue and yellow are complementary colors. Complementary colors are harmonizing colors, one heightening the effect of the other. Iron in the sand used for making glass imparts to the glass a green color. Manganese added to glass produces a purplish red color. When both are added, colorless glass is pro-

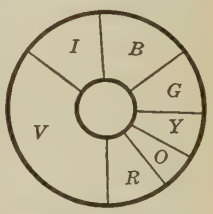


FIG. 515. — Disc for synthesis of light.

duced, since these colors are complementary. White goods acquire a yellow tint after they have been laundered. Since blue is the complement of yellow, "bluing" is used to whiten the wash.

435. The Primary Colors. Since sunlight is composed of seven colors which cannot be analyzed further, these seven colors are sometimes known as *elementary colors*. We have already learned that they combine to produce white light.

Experiment shows that white light may also be produced by combining any two complementary colors. *Three colors* have been found that will produce not only white light, but if they are combined in the right proportions, *any* color can be formed. Hence they are called *fundamental* or *primary colors*. The primary colors are *red*, *green*, and *bluish-violet*.

By the use of Von Nardroff's color apparatus, the effects of mixing the different primary colored lights may be shown. By means of a lantern white light may be thrown upon a screen through three round openings in the color apparatus. In each opening we may place a glass slide. One is colored *red*; a second, *blue*, or *bluish-violet;* and the third, *green*. Note that these are the three *primary colors*. The slides may be so moved in this apparatus that the inner edges overlap, as shown in Fig. 515a. Where the three overlap, the three primary colors combine to produce white light. The overlapping of the green and red produces *yellow*; of the red and blue, *purple* or *crimson*; and of the blue and green, *blue-green*, or *peacock-blue*. If we use the blue and yellow together without the other colors, we have white light, since they are complementary. Taking yellow from the white leaves the blue, which is opposite in the figure. In the same manner, taking red light from white leaves

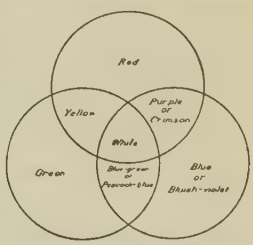


FIG. 515a. — How colors combine.

the blue-green or peacock-blue; taking green from white light leaves the color shown opposite in the figure, purple, or crimson.

436. Theory of Color. It is of interest to inquire how light waves of different length affect the eye in such a manner that we see different colors. The most generally accepted theory of color sensation was proposed by Dr. Thomas Young and later elaborated by Helmholtz. It is based upon the *three primary colors.* According to the Young-Helmholtz color theory, the retina of the eye is provided with three sets of nerves, each set being sensitive to one of the three primary colors.

If all three sets of nerves are equally stimulated, we receive the sensation of white. Of course blackness or darkness is the result of no stimulation. When red waves enter the eye, they stimulate *chiefly* the nerves that produce the sensation of red, and we see that color. If only those nerves that are sensitive to green are stimulated, the sensation of green is produced in the brain. When yellow light enters the eye, both the red and the green sets of nerves are stimulated. The brain identifies purple, if the nerves sensitive to red and bluish-violet are both stimulated. Thus all the colors and shades are produced by the unequal stimulation of these three sets of color nerves.

437. Color Blindness. No one would care to ride on a train if the engineer could not tell any difference between red and green lights. Since there are some persons who are color blind, railroad companies give an examination to engineers and firemen to find out whether they can distinguish colors. To pass the tests, each man must match certain skeins of colored yarn. In some states such an examination is required before one can obtain an automobile driver's license. In the eye of a person who is color blind, one or more of the three sets of nerves that are sensitive to colors is lacking. In some cases two sets of nerves are lacking, and

in rare cases, all three sets. In such extreme cases, the person's eye is sensitive to lights and shadows only.

The poet Whittier is said to have patched a green wallpaper in his library with a bright crimson pattern. John Dalton, who was a Quaker, at one time appeared on the streets wearing red stockings; to him they appeared gray. He was the first to study this defect in the eye. Hence color blindness is sometimes called Daltonism. About 4% of men are color blind, but not more than one woman in 200 has this defect. Of course a person who is color blind cannot distinguish between red cherries and green, and he is not fitted to pick strawberries. This defect is usually congenital, and there is no cure for it. Some cases appear to have been caused by the use of tobacco or alcohol.

438. Retinal Fatigue. Possibly most pupils have had the following experience: After reading in strong sunlight the outside page of a newspaper printed on pink paper, one finds that the inside page of white paper appears green. We may suspend a bright red disc on a white background in strong sunlight. After each pupil has looked intently at the disc for about one minute, he will see a green spot the size of the disc when he looks at the white background. This phenomenon is due to *retinal fatigue.* The retina of the eye tires of red and refuses to be stimulated by it any longer; the other six colors reflected by the white background combine to produce the green color. Red and green are complementary colors. When we repeat the experiment, using a blue disc, the spot that appears after the eye tires of blue, is yellow.

439. Mixing Pigments. When we *add* blue and yellow *light*, we have white light produced. If we mix a blue *pigment* with a yellow one, we do not have white produced, but green. Each pigment *subtracts* certain colors. For example, the yellow *subtracts* or absorbs blue and violet, and the blue *subtracts* or absorbs red and yellow. Green is the only color

that is not subtracted by either pigment; hence these two pigments produce green.

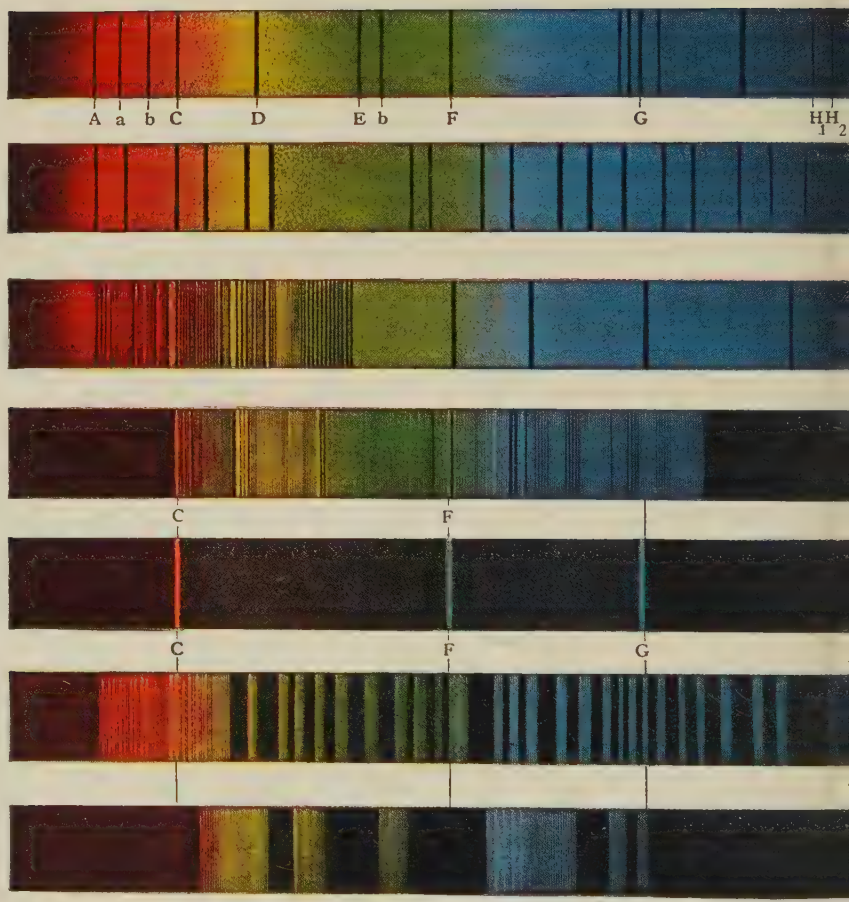
When we mix pigments, each one always subtracts certain colors from white light; the resulting color depends upon the light waves that are not absorbed. The *primary pigments* are the complements of the three primary colors. They are, respectively, *peacock blue* (red), *crimson* (green), and *yellow* (bluish violet). When the three primary pigments are mixed, all the colors are subtracted from white light, and the mixture is black.

440. Three-color Printing. In three-color printing, three negatives of the same object are made through three color screens, each stained with one of the three primary colors. Halftone blocks are then made from these negatives in the usual manner. The colored plate is then printed on white paper, first with yellow ink, then with red, and finally with blue. The accuracy of the color reproduction depends upon the selection of inks of a shade exactly complementary to those shades used in making the color screens. (See Frontispiece.)

441. Kinds of Spectra. We know that the sun's rays are separated into colors by a prism to form a solar spectrum. Light from other sources may be analyzed in the same manner. There are three kinds of spectra:

(1) *Continuous.* A platinum wire held in the colorless flame of a burner produces a spectrum that consists of an *unbroken band of seven colors.* Since the seven colors form one unbroken band, such a spectrum is said to be *continuous. Continuous spectra are produced by incandescent solids, liquids, and dense gases.*

(2) *Discontinuous.* Let us dip a platinum wire into a solution of common salt, or sodium chloride, and then hold the wire in the colorless flame of a burner surrounded by a piece of metal in which a narrow slit has been cut. When the light coming through this slit falls upon a prism, the spectrum which it forms on a screen consists of a single line of a



Spectra of the Fixed Stars and Nebulae Compared with the Sun-Spectrum and Other Spectra

bright yellow color. *Luminous gases or vapors under atmospheric pressure give bright line spectra.* Such a bright yellow line in a spectrum is characteristic of all compounds that contain sodium. When the spectrum produced by the hot platinum wire and the luminous sodium vapor are examined together, we find that the platinum produces the band of colors, but that the sodium vapor gives a bright line in the yellow of the spectrum. It always appears in a certain part of the spectrum. Since this bright line breaks the continuity of the band of colors, such *bright line* spectra are known as *discontinuous spectra.* Luminous vapors containing compounds of calcium produce two bright lines, one in the green and the other in the red. The spectral chart opposite this page shows the three bright lines produced by hydrogen.

(3) *Absorptive.* We may produce bright line spectra with luminous sodium vapor just as before, and then place an iron pan containing sodium chloride between the slit and the prism, as in Fig. 516. When the pan is heated enough to vaporize the sodium chloride, but not hot enough to make it luminous, a dark line appears in the spectrum where the yellow line had previously appeared. The yellow light waves have been *absorbed* by the sodium vapor. Such spectra are called *dark-line,* or *absorptive spectra. Gases or vapors can absorb light waves of the same length they would produce themselves, if they were heated to luminosity.* For example, *luminous* sodium vapor gives bright yellow light waves. *Non-luminous* sodium vapor absorbs yellow light waves.

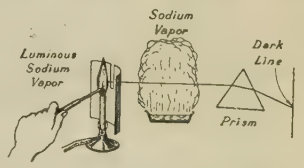


FIG. 516. — Absorptive spectra.

442. Fraunhofer Lines. As early as 1802, Wollaston noticed that certain dark lines appear in the sun's spectrum, when produced by a prism and a narrow slit to admit the sun's rays. Ten years later they were independently discovered by Fraunhofer, who charted a large number of these dark

lines. He observed that they always appear in the same position in the spectrum, and that the position is the same as that occupied by the bright lines caused by the luminous vapors of different elements. Since about 600 of these lines were charted by Fraunhofer, they are known as *Fraunhofer lines*.

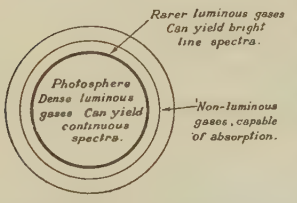

Rarer luminous gases Can yield bright line spectra.
Photosphere Dense luminous gases Can yield continuous spectra.
Non-luminous gases, capable of absorption.

FIG. 517. — Why sun yields absorptive spectra.

From a consideration of Fig. 517, we can understand why the sun produces absorptive spectra. The photosphere consists of highly compressed gases, which would form continuous spectra if the sun had no atmosphere. The chromosphere consists of luminous gases under less pressure. They would produce bright line spectra, if they could be examined alone. In the outer portions of the sun's atmosphere, there are undoubtedly non-luminous vapors which absorb the waves that might produce bright line spectra. Hence the sun yields absorptive spectra. Better methods of producing a long spectrum have been produced than those used by Fraunhofer. In such a spectrum the number of lines is almost unlimited.

443. The Spectroscope. The spectroscope is an optical instrument used for examining spectra. It consists of a prism P, Fig. 518, mounted on a circular protractor. The collimator tube C receives light through the slit S and transmits it through the lens L so that the rays are parallel as they strike the prism. A small telescope T magnifies the spectrum which is produced by the prism. Cross-threads in the telescope may be focused on any line in the spectrum. Both the collimator tube

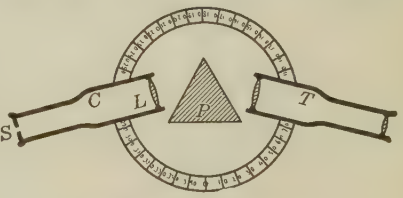


FIG. 518. — Spectroscope.

and the telescope are mounted on a circular protractor, so the angular position of any line may be carefully measured.

444. Spectrum Analysis. Although Fraunhofer charted some of the dark lines in the solar spectrum as early as 1812, it was not until 1859 that the spectroscope began to be used for the analysis of elements. At that time Bunsen and Kirchoff, two German chemists, introduced the use of the spectroscope for analytical work. We have seen that sodium compounds always give a bright yellow line when examined by a spectroscope. This test is so delicate that less than one millionth of a milligram of sodium can be detected by means of the spectroscope. Several elements have been discovered in this way. In 1860 Bunsen discovered *cæsium* and *rubidium* by the use of the spectroscope. The former is so named because it gives two blue lines in the spectrum, and the latter because it yields two red lines. About two years ago Professor Hopkins of the University of Illinois discovered a new element, which he named *illinium*.

As early as 1868 helium was discovered in the sun's atmosphere by Sir Norman Lockyer. It was not discovered in the earth's atmosphere until 1895. By means of the spectroscope, astronomers are able to determine the composition of the sun and other celestial bodies.

445. The Rainbow. When the sun shines upon drops of falling water, a solar spectrum may be formed. Water disperses light in the same manner as a prism, but reflection and refraction of light are also important in forming the rainbow. Fig. 519 shows the path that a beam of sunlight takes in passing through a drop of water. As it enters the drop at A it is refracted; dispersal also occurs. The red ray suffers total reflection at R and the violet at V. When they leave the drop at B both rays are again refracted. The angle these refracted rays make with the horizon of an observer as he stands with his back to the sun is 40° for the violet, and 42° for the red rays. In the actual bow which the observer

sees the red rays come from drops of water at an angle of 42°, and the violet from those at an angle of 40°. The other colors are formed by drops between these angles. The rainbow is an arc, since the eye of the observer is at the tip of a cone from which he sees the colored rays refracted from drops in all directions at angles of from 40° to 42°.

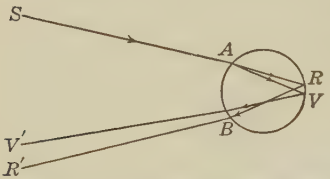


Fig. 519. — Rainbow produced by refraction, total reflection, and dispersion.

Sometimes a larger *secondary* bow is seen above the *primary*. The colors are here reversed, the violet being on the outside. The light is refracted from drops of water at an angle of from 51° to 54°. It enters the lower part of the drop, is refracted and dispersed as in the primary bow, but it is *twice totally reflected* before it leaves the drop. For this reason more light is absorbed, and the secondary bow is always fainter than the primary bow.

446. Chromatic Aberration. Light passing through the edge of a lens undergoes spherical aberration. In our experiment with the prism we learned that different colors have different indices of refraction; therefore light is also dispersed in passing through a lens. Since the violet light is bent more than the other colors, it is brought to a focus more quickly. (See Fig. 520.)

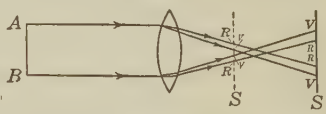


Fig. 520. — Chromatic aberration.

A screen placed at S shows an inner ring of violet surrounded by the other colors. If the screen is moved to the position S', the inner ring will be red. Images formed by ordinary spherical lenses are always fringed with spectral colors. *The nonfocusing of light of different colors is called chromatic aberration.*

447. Achromatic Lenses. The fringe of colors around the image formed by an ordinary lens is annoying. It re-

tarded the progress in the use of optical instruments until the latter part of the eighteenth century, when Dolland discovered that chromatic aberration may be remedied by using a combination of lenses. *Achromatic* (without color) lenses produce images with no fringe of colors. As shown in Fig. 521, they generally consist of a double convex lens made of crown glass and a plano-concave lens made of flint glass. Such a combination of lenses corrects dispersal without preventing refraction. High-grade optical instruments are fitted with lens combinations that are corrected for both spherical and chromatic aberration.

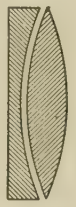


FIG. 521. — Achromatic lens.

448. Interference. Just as one sound wave may be superimposed upon another to strengthen or diminish sound, so light waves may interfere with one another. A wedge-shaped film of air between two pieces of glass, one plane and the other slightly convex, may be used to illustrate this phenomenon. Both pieces of glass reflect a part of the light. It is possible to have the air film of such thickness that the two reflected rays meet either in opposite phases or in the same phase. If a sodium flame, which gives yellow light only, is used, the rays meeting in opposite phase will interfere and produce a dark band; those that meet in the same phase will intensify the light, producing a bright yellow band. When sunlight is used, bands of spectral colors are produced, since the air film is wedge-shaped and the wave lengths corresponding to different colors interfere at different positions. The air film between oil and water, or in a cracked piece of ice or glass, shows spectral colors when it is viewed from an oblique angle. The light waves reflected from the two surfaces which are separated by the air film meet in opposite phases, thus producing spectral colors by interference.

449. Diffraction. When the wave theory of light was proposed, its opponents argued that light waves should not

cast shadows, but should bend around corners as sound waves do. Experiment shows that very short sound waves do cast shadows to some extent, and that light waves under certain circumstances do bend out of their course slightly. When light is transmitted through an opening that is small in comparison with its wave length, the wave spreads out and produces spectral colors by interference. This phenomenon, which is known as *diffraction*, may also be produced by reflection of light from an opaque surface that is striated.

By means of a diamond point, 15,000 to 30,000 lines to the inch have been ruled on glass, or on speculum metal. Such a ruled plate is called a *diffraction grating*. With a glass grating, light is transmitted through the narrow space between the lines and spreads out, or is diffracted. Such a grating is much better than a prism for examining spectra, since the colors do not overlap and the spectrum that is produced may be several feet in length. The plumage of some birds, and some changeable silks have a beautiful play of colors on account of diffraction.

450. Polarization. Sound waves are longitudinal; light waves are transverse vibrations of the ether in all directions. Fig. 522 *A* may be used to represent a cross-section of a beam of light with a few of the directions of vibration included. If all the vibrations are in one plane, as in Fig. 522 *B*, we call it a *plane of polarized light*. Certain crystals, tourmaline, for example, have the property of transmitting *only* those light waves whose plane lies in the same direction as the axis of the crystal. Fig. 523 *A* represents two tourmaline crystals with their axes parallel. A complex beam of light enters the first crystal at *A* and is polarized, passing through both crystals in the plane of their axes. In Fig. 523 *B*, the

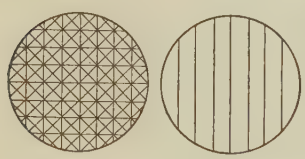


FIG. 522. — *A*. Possible appearance of end of beam of light. *B*. Of polarized light.

beam is polarized by A in exactly the same manner. The axis of B, however, is turned perpendicular to the plane of light; therefore no light is transmitted. The tourmaline

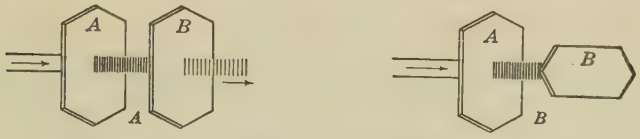


FIG. 523. — Effect of tourmaline crystals.

tongs of Fig. 524 illustrate polarization. Either crystal used alone transmits light, but when their axes are at right angles, all light is intercepted. The vibrating rope shown in Fig. 525 also serves as an illustration.

The *polariscope* is constructed on the same principle. One crystal polarizes the light; it is called the *polarizer*. The other crystal, which is called the *analyzer*, may be readily rotated. Some substances have the ability to twist or turn the plane of polarized light. Glucose, sugar, and many organic substances have this property. Suppose we have the two crystals of a polariscope turned as in Fig. 523B so that no light passes, and a sugar solution is then placed between them. The sugar solution turns the plane of polarized light to such an extent that it will again pass through the analyzer. The analyzer must now be rotated a certain number of degrees in order to intercept this twisted plane. The amount of rotation required depends upon the kind of substance used and upon the strength of the solution. Substances that turn the plane to the right are called *dextrorotatory*. Dextrose is an example. Substances that twist

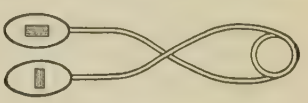


FIG. 524. — Tourmaline tongs.

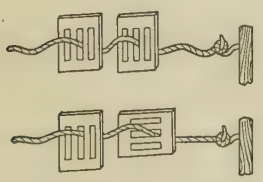


FIG. 525. — Rope vibrations to represent polarization.

the plane to the left are called *levo-rotatory*. Levulose is an example. The polariscope is used to test the strength and purity of substances, especially of sugars.

SUMMARY

Since light waves of different color have different refrangibility, light is scattered or dispersed by refracting media. Dispersal from raindrops produces the rainbow. The dispersion of light by lenses which produce a color-fringed image may be remedied by the use of achromatic lenses.

Color is analogous to pitch; it depends upon the length of the light waves, or upon the frequency of vibration. The color of an opaque object depends upon the color of the light it receives and upon the color of the light it can reflect. Any two colors that combine to produce white light are complementary.

Incandescent solids, liquids, and compressed gases yield continuous spectra; luminous gases produce bright-line spectra. Gases absorb light waves of the same length they would emit if heated to luminosity.

QUESTIONS

1. What do we mean when we say an object is red?

2. The Cooper-Hewitt mercury vapor lamp is deficient in red rays. What effect does its light have upon the appearance of persons in a room where it is used?

3. Doppler's principle applies to light waves. A luminous body moving toward the earth has its light waves shortened. Would the lines of its spectrum be displaced toward the violet end of the spectrum or toward the red?

4. Do two persons see the same rainbow? Explain.

5. Why is the rainbow curved? Can the complete circle ever be seen?

6. Do you think it is possible to have a rainbow at noon in July? Is a rainbow at noon possible in January? How would the latitude of a place affect your answer?

7. Does iron which is heated white hot give off red rays of light? How could you prove your answer?

8. If black objects absorb all the light they receive, how is it that we see them?

9. What color do objects appear when viewed through a piece of red glass?

10. How would your school colors appear if viewed through a piece of blue glass? If viewed through a piece of red glass? How does the American flag appear when viewed through blue glass? If it is viewed through red glass?

11. If a lady has a sallow or yellowish complexion, what color can she add to her face powder to neutralize the yellow tint?

12. Why is it undesirable to use blue paper, a blue rug, or blue draperies in a room that has a northern exposure? What colors may be used?

13. For selecting colors, the so-called daylight bulb is used. The bulb is tinted blue. Explain.

14. What color does a blue serge suit appear when examined by artificial light? Explain.

15. A ribbon which appears blue by daylight may seem green when viewed by artificial light. Explain.

16. In what ways has the introduction of spectrum analysis been very important?

17. Why should an applicant for a license to drive an automobile be required to pass a test for color blindness?

18. Why does milk lose its rich color when put in glass jars or bottles which have a green color?

19. Which colors are restful to the eye, and which colors are irritating if viewed for some time?

CHAPTER 21

MAGNETISM

A. NATURE OF MAGNETISM

Vocabulary

Declination, angular deviation of the compass needle from the true North.
Permeable, readily conducting magnetic lines of force.
Residual (*residue*), a part remaining.
Induction (*induco*—I lead in), the act or process by which a body becomes magnetized or electrified by the presence of a magnetized or electrified object.

451. Natural Magnets. In the Adirondacks of New York State and in certain other localities, beds of iron ore are found that have the property of attracting pieces of iron or steel. This black iron ore is called *magnetite.* The name was probably given by the Greeks, who discovered this ore in Magnesia, Asia Minor. When elongated pieces of magnetite are suspended by a thread so that they may take any position, they swing around until they assume a north-and-south line. For this reason they are called *lodestones* (leading stones). As early as the twelfth century, lodestones began to be used in Europe to indicate directions.

452. Artificial Magnets. Probably before the Christian era, the ancients had learned that iron could be magnetized by rubbing it on a piece of lodestone. At the present time the lodestone is little used, since *artificial magnets* are much better than natural ones. If we wish to make a magnet, we can do so by stroking a piece of steel with a magnet, as shown in Fig. 526. We must be careful to begin always at the same end and to bring the magnet back through the air to the starting point. There are other ways of making magnets.

In a later chapter the student will learn how to make a temporary magnet by passing an electric current through a wire wound around a bar of steel or iron.

453. Magnetic and Non-magnetic Materials. Everyone knows that a magnet will attract pieces of iron or steel. These substances are called *magnetic materials.* Cobalt and nickel are also attracted by a magnet, though to a lesser degree. A few alloys have been made that are magnetic, but in almost all cases either iron or steel is used when a magnetic material is needed.

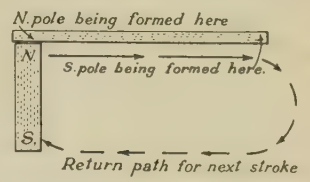


FIG. 526.—How to make a magnet.

Most substances, such as wood, copper, glass, aluminum, etc., are *non-magnetic.* They are not affected in any way by the magnet. A few substances, antimony, tin, bismuth, and zinc, for example, are actually repelled by the magnet. They are said to be diamagnetic.

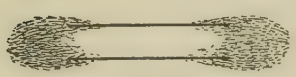


FIG. 527. — Polarity.

454. Polarity. If we sift some iron filings on a piece of paper, lay a bar magnet in the filings, and then lift the magnet, we find that the filings cling to the magnet at or near the ends only. (See Fig. 527.) The magnetic force appears to be concentrated at or near the ends of the magnet. Probably more filings will be found about one centimeter from each end than at any other place, if the bar used is about six inches in length. These points at which the magnetism appears to be concentrated are called *the poles of the magnet.*

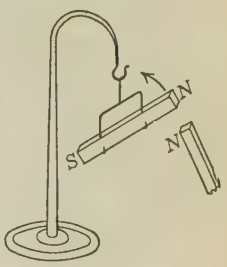


FIG. 528. — Like poles repel.

If we suspend a bar magnet as in Fig. 528 so that it can swing freely, it finally comes to rest with its ends pointing

in a nearly north and south direction. That pole of a freely swinging magnet which points to the north is called a *north-seeking pole;* it is also called merely a north pole, the N-pole, or the + pole. The other pole is called the *south-seeking pole;* it is also known as the south pole, the S-pole, or the −pole.

455. Laws of Magnets. When the N-pole of a magnet is brought near the N-pole of another magnet, suspended as in Fig. 528, repulsion occurs; if the two S-poles are brought near one another, they also repel. If we hold the N-pole near the S-pole of the suspended magnet, the two poles attract. These experiments verify the law of polarity: *Like poles repel; unlike poles attract.* The force of attraction is directly proportional to the product of the strengths of the poles and inversely proportional to the square of the distance between them. (Compare with the law of gravitation.) A pole is said to be of unit strength when it repels an exactly similar pole one centimeter distant with a force of one dyne.

456. The Compass. Since a magnetized needle that is free to take any position swings around into a nearly north-and-south line, such a needle balanced on a pivot may be used as a compass to show directions. (See Fig. 529.) The use of such a needle to indicate directions has made navigation much safer than it was before the invention of the mariner's compass. The student knows from his study of history that the explorations that led to the discovery of America followed shortly after the use of the compass be-

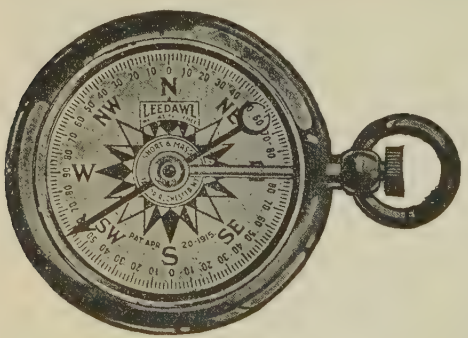


Fig. 529. — Compass.

came common. Of course the compass needle is not an infallible guide, since it is influenced by beds of iron ore and large masses of iron; it does not point to the *true north* in the majority of places on the globe.

457. Temporary and Permanent Magnets. When a piece of *soft* iron is stroked with a magnet, it is *easily* magnetized. But in a short time, the iron loses nearly all its magnetism. Hence a magnet made of soft iron is only a *temporary magnet*. When it is necessary to magnetize a piece of iron quickly and to have it lose its magnetism quickly, we use soft iron or some alloy. Silicon steel is an alloy that loses its magnetism quickly; it has little *retentivity*. It finds use in making the cores of electro-magnets. When the current is on, the core becomes magnetized quickly, but it loses its magnetism almost immediately when the current is turned off. Permalloy, made of nickel and iron, is more easily magnetized and demagnetized than any known substance. A little magnetism, known as *residual magnetism*, is usually retained in such cases.

It is much more difficult to magnetize a bar of steel, but it retains its magnetism a long time. Steel is used for making the so-called *permanent* magnets. We say steel has high *retentivity* because it is hard to magnetize and hard to demagnetize. Tungsten steel is especially difficult to magnetize, and its retentivity is very high.

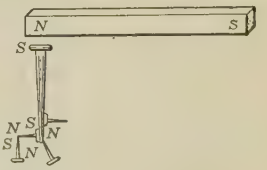


FIG. 530. — Magnetic induction.

458. Magnetic Induction. If we hold a bar magnet *near* or *in contact with* a soft iron nail, as in Fig. 530, the nail becomes a magnet by *induction*. As long as the bar magnet is held near the nail, it retains its magnetism, and several tacks may be picked up; if the bar magnet is removed, the tacks fall off. *Magnetism produced in this manner by the presence of a magnet is called induced magnetism.* By the use

of a small compass needle it may be shown that the nail is a magnet while the bar magnet is near it or in contact with it. Each tack also becomes a small magnet. The end of the nail near the north-seeking pole of the magnet becomes an S-pole, and the more remote end becomes an N-pole. When iron filings cling to a bar magnet, each filing becomes an independent magnet by induction. Any piece of iron becomes a temporary magnet in this manner when brought near a magnet.

459. Lines of Force. If we place a smooth piece of cardboard over a bar magnet, sprinkle iron filings evenly over the cardboard, and then tap the board gently, the filings will arrange themselves along curved lines known as *lines of force.* If we could get an independent N-pole (without the S-pole) and place it at the north-seeking pole of a magnet, it would move along a curved line from the north-seeking pole to the south-seeking pole of the magnet, as shown in Fig. 531. *The path that an independent N-pole would take in moving from the N-pole to the S-pole of a magnet is known as a line of force.* Of course the north-seeking pole is repelling this independent N-pole, and the south-seeking pole is attracting it, in each case with a force inversely proportional to the square of the distance between them.

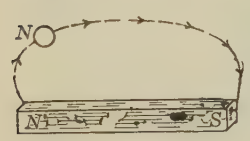


FIG. 531.— Line of force.

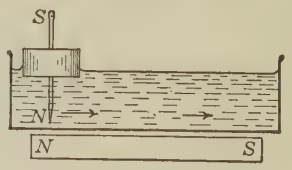


FIG. 532. — Path of floating magnetic pole.

It is not possible to get an independent N-pole, but by using a Mayer's floating magnet, consisting of a magnetized needle thrust through a cork so it will float vertically, as in Fig. 532, the result is essentially the same. If we place a bar magnet under the trough, the path taken by the floating magnet is practically the curve shown in Fig. 531.

460. Magnetic Field. If we wish to use a compass needle, we must remove all pieces of iron to a distance of a meter or more. The lines of force of a magnet extend out to some distance from the magnet. Any space permeated by lines of force is a *magnetic field.* Such a magnetic field is influenced by any magnetic material brought within the field, and it produces an inductive effect upon the magnetic material. A field of unit strength has one line of force, called a *maxwell*, per square centimeter. The area is always considered as perpendicular to the line of force. A magnetic field of unit intensity is called a *gauss.*

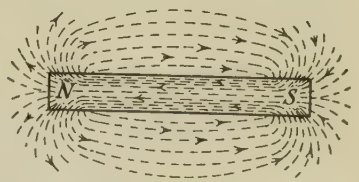


FIG. 533. — Lines of force about a magnet.

A permanent chart of a magnetic field may be easily made by pinning a blue-print paper over a magnet which rests in a grooved board, and sifting iron filings over it. When the board is tapped gently, the filings arrange themselves in the direction of the lines of force. After exposure to the light for a few minutes, the print is developed in the usual manner. Fig. 533 shows the field of force about a single bar magnet. If two magnets are used with like poles adjacent, the flexibility of the lines of force is clearly indicated. We notice also that the lines of force repel one another. (See Fig. 534.) They really act like elastic bands stretched from pole to pole of the magnet. If we use two magnets with unlike poles adjacent, then the lines of force appear to pass from the north-seeking pole

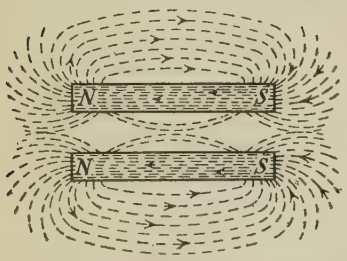


FIG. 534. — Lines of force. Two bar magnets.

of one magnet to the south-seeking pole of the other. (See Fig. 535.)

461. Properties of Lines of Force. From our study of lines of force we may make a summary of their properties:

1. According to the conception of physicists, the lines of force are *closed curves*, extending from the north-seeking to the south-seeking pole through the air, and returning through the magnet.

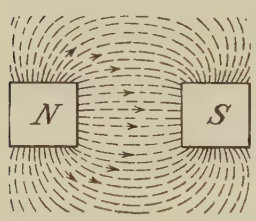


Fig. 535. — Two bar magnets. Unlike poles adjacent.

2. They do not cross one another, but they repel one another. Hence they are farther apart opposite the center of the magnet.

3. We find the lines of force concentrated at the poles; thus they show that the magnetic field is much stronger at or near the poles. They actually picture the direction in which the magnetic force acts.

While such lines of force may seem to the beginner to be quite visionary, yet he will find that they play an important part not only in magnetism, but also in practical electricity.

462. Magnetic Transparency and Permeability. In § 460 we learned that magnetic force exerts its influence upon iron filings *through* blue-print paper. Let us repeat the experiment, covering the magnet with sheets of various metals in turn. We find that copper, tin, lead, zinc, wood, glass, aluminum, and various other substances do not hinder at all the passage of the magnetic force through them. The filings seem to be affected as readily as if the substances were not present. We conclude that all these substances are *transparent* to magnetism, just as glass is transparent to light. In all cases we have used non-magnetic materials.

Let us repeat the experiment, using a sheet of iron between the magnet and the filings. The iron is not transparent to magnetism. The lines of force do not *cross* the iron; they

enter the iron readily and follow a path within the iron itself. Fig. 536 shows the lines of force passing across the air-gap between the two poles of a horseshoe-shaped magnet. In the same figure, we see the effect of introducing an iron ring

FIG. 536. — Permeability of soft iron. Note effect of ring on lines of force.

between the two poles. The lines of force prefer the iron to any other medium. We say that iron is very *permeable*, since it readily *gathers in* lines of force and affords an excellent path for their transmission.

463. The Shape of a Magnet. From a study of the examples of permeability, we can understand why magnets are usually made in the shape of a horseshoe, rather than that of a straight bar. Suppose we bend a bar magnet until the two ends are quite close together. The air-gap between the two poles has been very much decreased. The intensity of the field is much greater, due to the concentration of the lines of force. Compare the concentration of the lines of force about a bar magnet, Fig. 533, with that of a horseshoe magnet, Fig. 537*A*. When the armature is used with the horseshoe magnet, as in Fig. 537*B*,

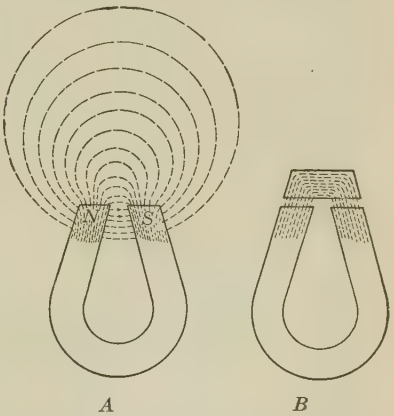


FIG. 537. — *A*. Horseshoe magnet. *B*. Effect of armature.

the effect of the high permeability of iron is shown. Few lines of force enter the air at all. When a magnet is not in use, the armature should always be kept across the poles to conserve the strength of the magnet.

464. Theory of Magnetism. The force of magnetism seems very mysterious. Experimental work leads us to believe that each molecule is a small magnet with an N-pole and an S-pole. Suppose we break a bar magnet. We do not destroy its magnetism, but we have two magnets formed with two poles each. (See Fig. 538.) We may continue to break the magnet into smaller pieces, but each small piece still has polarity.

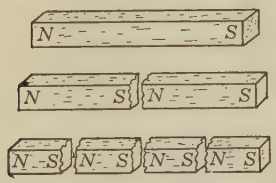


Fig. 538. — Effect of breaking a magnet.

In an unmagnetized iron bar the molecules are probably arranged as in Fig. 539*A*, so haphazard that they mutually neutralize one another. If we lay two bar magnets of equal strength side by side with unlike poles adjacent, each neutralizes the effect of the other. Hence a bar of iron that has its molecules in such a miscellaneous grouping shows no polarity.

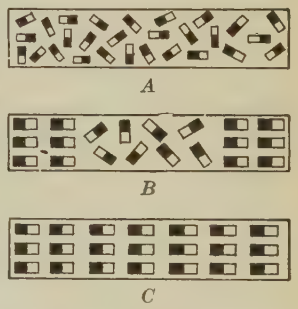


Fig. 539. — *A*. Unmagnetized bar. *B*. Partially magnetized. *C*. Saturated bar.

Now let us move a magnet along this bar, stroking it from left to right with the S-pole of the magnet. Each time we stroke it in this manner, some of the molecules will be twisted around in the bar so that they tend to arrange themselves in the position shown in Fig. 539*B*. The bar is now partially magnetized, and it shows some polarity. If we continue to stroke the bar with the magnet, in time all the molecules will be arranged with their N-poles toward the right

and their S-poles toward the left. The right-hand end of Fig. 539 *C* is the north-seeking pole of the newly magnetized bar.

465. The Facts Support the Theory. Several facts concerning magnetism furnish evidence that the theory of magnetism is correct.

1. The theory has just been explained by the manner of making a magnet. If we stroke the bar in the opposite direction, the polarity is reversed. In making a bar magnet, we must always begin at the same end to stroke the bar. If we stroked backward, we should disarrange the molecules.

2. If we wish to destroy a magnet, we can do so by heating it to a red heat and then pounding it. The high temperature makes the molecules more mobile and they swing around into other positions more readily. Pounding or jarring it tends to disarrange the molecules.

3. If we fill a glass tube with iron filings and then stroke it with one end of a bar magnet, it shows polarity. Each filing seems to become a magnet. Shaking the tube disarranges the iron filings, and the magnetism is destroyed. In a like manner, each molecule of a piece of iron probably is an independent magnet.

4. This theory offers an explanation of magnetic induction. A magnet brought near a piece of iron pulls some of the molecules around until the iron shows polarity. Most of them swing back to their former position when the magnet is removed.

5. In a piece of soft iron, the molecules are probably much more easily turned around than they are in hard steel. We know that the iron is easily magnetized, but since the molecules are more mobile, they will be more easily jostled out of their regular position. Hence soft iron is easily magnetized and loses its magnetism easily. Steel is difficult to magnetize, but it retains its magnetism.

6. Let us magnetize a knitting needle and then heat it

red hot at a spot about two inches from one end. Now if we grasp the ends with pliers and twist sharply, the needle will be distorted at the spot where it was heated. After the needle has cooled, we find that iron filings will cling not only at the ends of the needle but also on either side of the spot that had been heated. *Consequent poles* are developed in this manner by the disarrangement of the molecules at some spot in the magnet.

B. TERRESTRIAL MAGNETISM

466. The Earth as a Magnet. William Gilbert, the physician of Queen Elizabeth, was the first Englishman to use experimental methods in order to test certain theories. As early as 1600 A.D. he published *De Magnete*, a work containing many interesting facts that he had learned by his experiments. Gilbert fashioned out of lodestone a small sphere which he called "terrella," or "little earth." When he placed small pivoted magnetic needles at different positions on this sphere, he found that their behavior was quite similar to that of magnetized needles at corresponding places on the earth's surface.

The earth in its effect upon magnetized objects and magnetic materials acts as if it were a huge magnet. Its lines of force appear to be concentrated at the earth's magnetic poles. In fact the earth acts as it would if a large bar magnet 8000 miles long extended through the earth from one magnetic pole to the other. The magnetic pole of the northern hemisphere has been discovered at about 70° North Latitude and 96° West Longitude. We may think of this pole in two ways. If we consider it the earth's North Magnetic Pole, then the north-seeking pole of a compass needle must be a south pole, since unlike poles attract. Otherwise we must think of the magnetic pole in the northern hemisphere as the earth's south pole and the north-seeking pole of the magnetic needle as a true north pole. The latter

is less logical, but the term north pole as applied to the north-seeking pole of a magnetic needle is much more commonly used. It matters little how one thinks of it, provided the student remembers that the term north pole, N-pole, or + pole refers to that end of a compass needle which seeks the north. The South Magnetic Pole of the earth has been

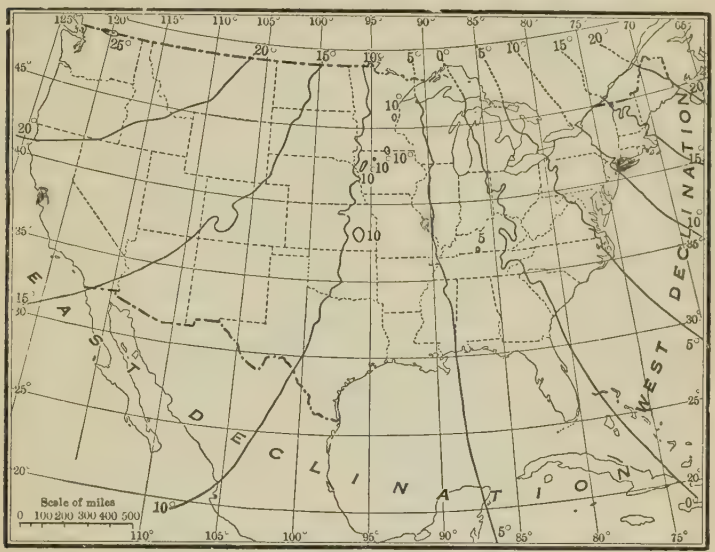


FIG. 540. — Chart of isogonic lines. *(Courtesy of U. S. Coast and Geodetic Survey.)*

discovered at about 72° South Latitude and 155° East Longitude. The earth's lines of force may be considered *magnetic meridians* extending from one magnetic pole to the other magnetic pole.

467. Magnetic Declination. If the earth's North Magnetic Pole and its North Geographic Pole were coincident, the north-seeking pole of a compass needle would everywhere point to the true north. Since the magnetic pole is about 20° south of the geographic pole, the compass may

point to the North Magnetic Pole without pointing to the true north, or to the North Geographic Pole. Columbus was the first to notice the variation of the compass needle in different localities. His sailors were so thoroughly alarmed by these variations of the needle that they threatened to mutiny and throw Columbus overboard. The angle between the true north, and the north as indicated by the compass needle, is called the *angle of declination; it is the angle of deviation of the magnetic needle from the true north.* Lines drawn through places on the earth's surface having the same declination are called *isogonic* lines. (See Fig. 540.) Lines drawn through places having no declination are called *agonic* lines. A line of zero declination passes through South Carolina, eastern Tennessee and Kentucky, Western Ohio, and Michigan. For places East of this line, the declination is West; for places West of the line, it is East.

The angle of declination varies slightly from year to year. In 1831 when the earth's North Magnetic Pole was found by Sir James Ross, it was located at 70° and 30′ N. Latitude, and 95° W. Longitude. In the year 1905 it was again located by Captain Amundsen almost 2 degrees farther West. Its position at that time was about 70° and 5′ N. Latitude, and 96° and 46′ W. Longitude. This slow westward migration of the magnetic pole causes the variation in the declination. Before a surveyor begins the survey of an unexplored tract of land, he establishes a north-and-south line and measures the declination.

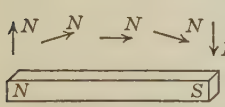


FIG. 541. — Magnetic dip.

468. Magnetic Inclination or Dip. If we place a small compass on a bar magnet and slide it along from one end to the other, it acts in the manner shown in the diagram of Fig. 541. Near the middle it is horizontal. It dips when placed at either end of the magnet.

A compass needle mounted on a horizontal axis so that its

dip may be measured is called a *dipping needle.* (See Fig. 542.) At places on the earth's surface midway between the magnetic poles, the dip is zero. A line drawn through places on the earth's surface where the dip of the needle is zero is called the *magnetic equator.* It is an *aclinic* line. Lines drawn through places having the same *dip* or *inclination* are called *isoclinic* lines. At the magnetic poles the needle stands at an angle of 90°, or in a vertical position.

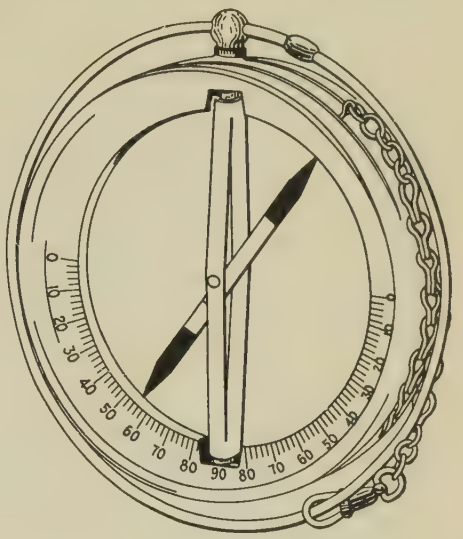


FIG. 542. — Dipping needle.

469. Inductive Action of the Earth. Pieces of iron which have been lying in contact with the earth for some time usually show some signs of polarity. This is especially apt to be true if they lie parallel to the earth's magnetic meridian. Since the earth acts as if it were a huge magnet, magnetic materials in contact with it are *magnetized by induction.* Let us hold an iron rod in the direction of the earth's meridian with the north end slanting down at an angle of about 70°. If we strike the rod a few blows with a hammer, it will when tested be found to have polarity. Now let us reverse the rod and strike it as before. When it is again tested for magnetism, the polarity is found to have been reversed. The rod may be demagnetized by holding it at right angles to the magnetic meridian (East and West) and striking it a few blows with a hammer.

SUMMARY

A magnet may be made by stroking a bar of steel with a lodestone, always beginning at the same end. Its magnetism may be destroyed by heating it, or by pounding it, if it is held at right angles to the magnetic meridian.

The magnetic force appears to be concentrated at or near the ends of the magnets at points called poles. The north-seeking pole of a freely swinging magnet seeks the North Magnetic Pole.

Like poles repel; unlike poles attract. A single line of force is called a maxwell. A line of force perpendicular to an area of one square centimeter gives a magnetic field of unit strength; it is called a gauss.

The earth is a huge magnet. It acts inductively upon magnetic materials near or in contact with it, magnetizing them.

The compass needle does not point to the true north at all places. The angle of deviation of the magnetic needle from the true north is called magnetic declination.

QUESTIONS

1. When bar magnets are held together with unlike poles adjacent, they show little attraction for magnetic materials. When held with like poles adjacent, the attraction is increased. Explain.

2. Iron posts and pillars are usually slightly polarized. Explain. Is the top an N-pole or an S-pole?

3. Why is polarity the best test for magnetism? Why is repulsion a surer test for magnetism than attraction?

4. If an iron bar attracts either end of a compass needle, is it magnetized? Give a reason for your answer.

5. If the balance wheel of a watch becomes magnetized, the watch fails to keep good time. How may the works of a watch be protected against magnetization?

6. Could Peary or Capt. Byrd have reached the North Pole by following the direction indicated by the north-seeking pole of a compass? Explain. In what direction would the north-seeking pole of a compass point from the North Geographic Pole?

7. In an unsurveyed territory, how could you find the true north? How could you find the magnetic declination?

8. How can a dipping needle be used to indicate the presence of beds of magnetic iron ore?

9. How would you expect the declination of the compass to be affected by the presence of large beds of magnetite?

10. Why is the gyro-compass now used on submarines and many battleships?

11. When not in use, two bar magnets should be packed in a box with unlike ends adjacent, and two strips of soft iron joining the poles. Why?

12. If one pole of a bar magnet will pick up half a dozen tacks, would you expect two magnets of the same size to pick up more tacks (a) when the magnets are held together with like poles adjacent? (b) when held together with unlike poles adjacent? Make the experiment.

13. In order to pick up magnetic materials with a horseshoe-shaped magnet, the armature of the magnet must first be removed. Explain.

14. Before one begins work with magnetic needles, why should all pieces of iron be removed from the immediate vicinity?

15. From the map given on page 511, determine what direction the north-seeking pole of a compass needle would point at (a) New York; (b) Columbus, Ohio; (c) St. Louis; (d) San Francisco.

16. Since tin is not a magnetic material, how do you account for the fact that a tin can is attracted by a magnet?

17. How would the sensitiveness of a compass needle be affected if it were enclosed in an iron case? Why is it impossible to use an ordinary compass in a submarine?

18. A ship made almost entirely of wood was sent out by the Carnegie Institute to make magnetic surveys. What are the advantages of such a ship, and why must such surveys be made from time to time?

CHAPTER 22

ELECTRICITY--STATIC OR FRICTIONAL

Vocabulary

Electroscope (*elektron*, electricity; *skopos*, spy), an instrument used to detect the presence of an electric charge or of electricity.
Insulator, a non-conductor of electricity.
Volt, the unit of electrical pressure.
Ampere, the unit of current strength.
Ohm, the unit of electrical resistance.

470. Historical. As early as 600 B.C., Thales, a Greek philosopher, is said to have discovered that a piece of amber which has been rubbed with flannel attracts small pieces of paper or pith, the soft spongy tissue that forms the central portion of the stem of certain plants. Nothing came from his discovery, and it seems to have been about 2200 years before any one discovered that *many* substances have the same property. About 1600 A.D., the Englishman, Gilbert, who studied the earth's magnetism from a small earth which he fashioned, made the discovery that other substances may act the same as amber in attracting light particles, and he gave the name *electricity* (from the Greek word for amber, electron) to the phenomena produced in this manner. He also showed that electricity and magnetism are not identical, although they have some properties in common. In 1672 Otto von Guericke constructed a crude electrical machine for producing electricity. It consists of a sphere of sulphur mounted on an axis. When this sphere is turned, the hand held against its surface becomes electrified. In 1752 Benjamin Franklin performed his well-known experiment with the kite, in which he showed that lightning and electricity

are identical. He gave us the terms *positive* and *negative* electricity.

471. Electricity Produced by Friction. Every student has noticed the crackling sound produced by stroking a cat's back in dry, cold weather. No doubt he has also produced an electric spark by shuffling his feet over a rug or carpet and then touching a radiator or some other metallic object. When a glass rod is rubbed with silk, it is also electrified. To show that the glass rod carries an electric charge, we may hold it near a pith-ball suspended by a silk thread. The pith-ball is first attracted and then repelled. (See Fig. 543.) The same effect is produced if we rub a piece of sealing wax with flannel, or a rod of vulcanite with catskin. It is interesting to note that the silk, flannel, and catskin, also show electrification when tested in the same manner.

FIG. 543. — Pith-ball electroscope.

472. Electricity Is of Two Kinds. Let us suspend an electrically charged glass rod, as shown in Fig. 544, and bring near it a similarly charged rod. The rod is repelled. If we bring near the suspended rod a piece of vulcanite that has been rubbed with fur, the two rods attract. From this experiment it is obvious that there are *two kinds of electrification.* The one produced on glass by rubbing it with silk is called *positive,* or *plus electricity;* the other produced on vulcanite by rubbing it with fur is called *negative,* or *minus* electricity. This experiment also teaches us that *like electrical charges repel* and *unlike electrical charges attract.*

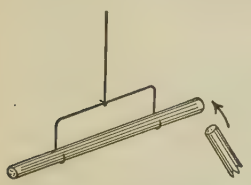


FIG. 544. — Repulsion between like charges.

473. The Electroscope. The pith-ball, which we used to detect the presence of an electrical charge, was first attracted by the glass rod; while they were in contact, the charge from the rod spread over the pith-ball until it became charged

with electricity of the same sign. Then repulsion occurred. The pith-ball electroscope is not nearly so sensitive as the instrument shown in Fig 545. A brass rod terminating in a ball or disc *A* is thrust through a rubber stopper. To the end *B* two strips of gold leaf or aluminum foil are attached, and the whole is then placed in a glass flask. An electrical charge applied to the ball or disc spreads to the leaves; since both leaves are thus charged with electricity of the same sign, they repel one another.

FIG. 545.— Simple gold leaf electroscope.

To avoid tearing the leaves by too intense a charge, a *proof-plane* is often used. It consists of a metal disc cemented to a rod of glass or vulcanite. (See Fig. 546.) In use the disc is applied to the charged object and then touched to the knob of the electroscope. A very efficient electroscope now used extensively in work with radio-active substances is shown in Fig. 547. Such *an instrument may be used to detect the presence of an electric charge, to determine its sign, or to measure its intensity.*

FIG. 546.— Proof-plane.

474. Conductors and Insulators. Let us support a brass ball by a silk thread and then connect it with an electroscope by means of a copper wire. (See Fig. 548.) When the ball *B* is charged electrically, the charge is transmitted along the copper wire to the electroscope, whose leaves diverge. Now let us replace the copper wire with a silk thread. A second charge applied to the ball is not transmitted to the electroscope,

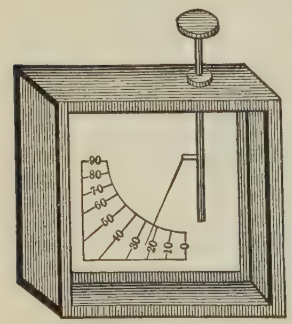


FIG. 547. — An electroscope.

and there is no divergence of its leaves. Materials which readily transmit an electric charge are called *conductors*. The metals are good conductors; especially silver, copper, aluminum, and iron. Materials which do not readily conduct an electric charge are called *insulators*. Glass, porcelain, shellac, resins, oils, silk, wool, sulphur, *dry* air, rubber, gutta-percha, bakelite, mica, and paraffin are among the best insulators. Since all substances offer some resistance to the passage of electricity through them, there are no perfect conductors. On the other hand, no insulator is perfect; hence the term "conductance" is a relative one. Cotton, dry wood, impure water, and acids, bases, or salts in water solution are sometimes called *semiconductors*. Pure water is an insulator.

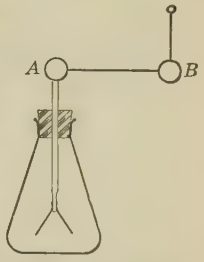


FIG. 548. — Conduction of electricity.

475. Franklin's Theory of Electricity. The mysterious force which we call electricity has caused philosophers to wonder. We know electricity best from a study of the effects that it produces. It rings door-bells, heats our percolators, drives our trolley cars, supplies us with light, and it may destroy animal life. Several theories have been advanced to explain the nature of electricity.

According to a theory proposed by Benjamin Franklin, electricity is a *fluid*. An object which is positively charged has an excess of electrical fluid; if an object has less electricity than normal, it is negatively charged. Just as heat is believed to flow from an object of high temperature to one of lower temperature, so it was considered by Franklin that electricity flows from the positive (plus) to the negative (minus). Although the *electron theory*, which is now generally accepted, clearly shows us that it is incorrect, we still follow the conventional diagrams introduced as a re-

sult of Franklin's theory, and assume that current electricity flows from the positive (+) to the negative (—). Some of the diagrams used in wireless hook-ups follow the modern theory and assume that electricity flows from the minus terminal to the plus.

476. The Electron Theory. The electron theory assumes that the atoms of all matter consist of both positive and negative electricity. From our study of the structure of matter, we know that all molecules are made up of atoms. According to the theory proposed by Dr. Bohr, the atoms always contain a positively charged nucleus. Positively charged particles are called *protons*. While there may be some negatively charged particles, or *electrons*, in the nucleus, yet it always has an *excess of protons*. Surrounding the nucleus, and revolving around it much as the planets revolve around the sun, are electrons. The hydrogen atom has a single planetary electron, while some of the heavy atoms have 90 or more. In the normal atom, the sum of the negative charges of the external electrons just equals the charge of the positive nucleus. Such an atom is neutral; it shows no sign of electrification. The sodium atom represented in Fig. 549 has a single electron in the outer ring. When it loses this electron, it acquires a positive charge. The symbol is Na; when it loses its outer electron, it has a plus charge; (Na^+). Fig. 550 represents a chlorine (Cl) atom which has seven electrons in the outer ring. It may gain one electron. Then it acquires a negative charge (Cl^-). The Na^+ may unite

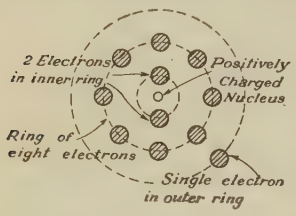


Fig. 549. — Sodium atom.

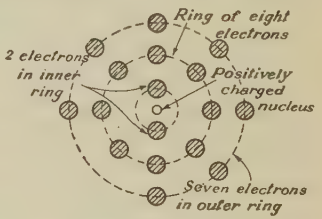


Fig. 550. — Chlorine atom.

with the Cl^- to form a molecule of NaCl, or common table salt.

When a glass rod is rubbed with silk, some of the electrons leave the glass and are transferred to the silk. The glass is now *deficient in electrons*, or it has a *positive* charge. The silk has an *excess of electrons*; hence its charge is *negative*. When we electrify a piece of sealing wax with flannel, the wax takes electrons from the flannel. The flannel has a positive charge, while the wax is negative. If we wrap the wax up in the flannel, and bring both near an electroscope, there is no sign of electrification. When they are separated again, the flannel shows a positive charge and the wax a negative one. For electrification, there must be either an excess of electrons, or a deficiency of electrons.

In this theory it is assumed that the protons are fixed, and that the electrons may be transferred. A current of electricity is a stream of electrons flowing through a conductor. These electrons flow from the hot filament of an audion tube to the plate and vary the current in our loud speaker. The mass and the speed of electrons have been determined. An electron weighs about $\frac{1}{1840}$ as much as the hydrogen atom. All electrons are alike. The differences in the properties of different elements depend upon the number and arrangement of the electrons that are present.

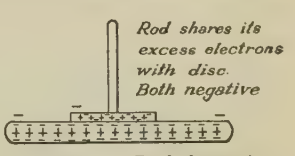


FIG. 551. — Rod shares its excess electrons.

477. Electrification. *a. By contact.* Suppose we have a rod of vulcanite charged with negative electricity. *It has an excess of electrons.* If we touch this rod with a proof-plane, some of the electrons from the rod will flow over to the proof-plane, as shown in Fig. 551. The rod shares its excess electrons with the proof-plane. We say the proof-plane has been charged by *contact*, or by *conduction*. If a proof-plane is brought into contact

with a glass rod, which had been charged positively, then electrons from the proof-plane will flow over to the rod to help equalize the rod's deficiency of electrons. Both will now show a positive charge. (See Fig. 552.) When an object is charged by contact, or conduction, it will always have a charge of the *same* sign as the object with which it was brought into contact.

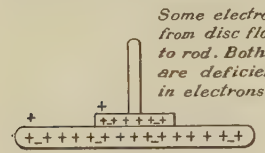


FIG. 552. — Charging by contact.

b. By induction. Let us next study the effect of bringing a charged rod *near* a conductor, but *not into contact* with it. The conductor AB of Fig. 553 is insulated from the earth. It has just sufficient electrons to neutralize its protons. Hence it is not electrified. A rod C, which has an excess of electrons (negative charges) is now brought near the conductor. Immediately the electrons are repelled to the remote end of the conductor. A charged rod brought *near* a conductor *induces* electricity of the *same sign* in the *remote* end of the conductor and electricity of the *opposite sign* in the *near* end of the conductor. When the rod is removed, the electrons spread over the conductor as before.

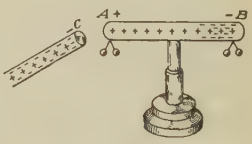


FIG. 553. — Charging by induction.

When we bring a *positively* charged rod near the conductor, then the electrons are attracted to the near end of the conductor, leaving the more remote end with a deficiency of electrons.

478. How to Charge an Electroscope by Induction. If we hold a negatively charged rod near the knob of an electroscope, as in Fig. 554*A*, the electrons are repelled and stream away from the knob to the leaves. Thus the knob is charged positively, and the leaves negatively. The leaves diverge widely, since both are charged with the same sign. If the rod is removed, the electrons will again distribute themselves

uniformly over the knob and leaves, and there will be no evidence of electrification.

Suppose, however, that we touch the knob with a finger while the rod is still held near the knob, as in Fig. 554*B*. Now the electrons will be repelled through the body, which is a fair conductor, to the earth. Since the electrons have been driven from both the knob and the leaves, they will

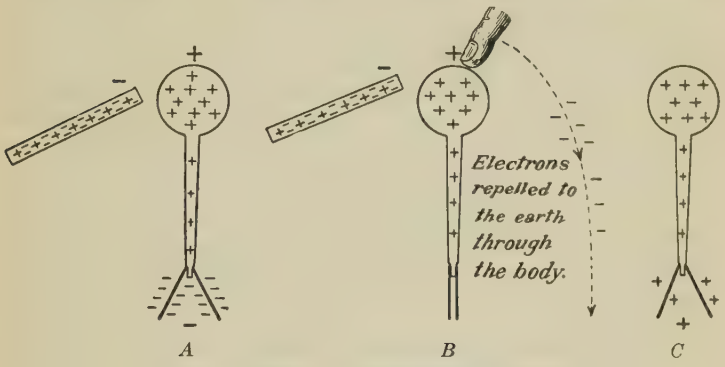


FIG. 554. — Charging an electroscope by induction.

be left with a positive charge. If the rod is removed while the finger still touches the knob, the electrons will return, and the electroscope will have no charge.

Instead of removing the rod while the finger still touches the knob, let us remove the finger *first*. The electrons were repelled to the earth through the body. The rod keeps them from coming back. Like charges repel. After the finger has been removed, the rod may then be removed, since the electrons do not readily return through the air, which is an insulator. The electroscope is now charged with *positive* electricity, as shown in Fig. 554*C*.

We can charge an electroscope *negatively*, if we hold a charged glass rod near the knob, touch the knob, and then remove the finger before the rod is removed.

A charged electroscope may be used to determine the sign of an electric charge. For example, a proof-plane is touched to the object of unknown sign and then brought in contact with the knob of a *positively* charged electroscope. If the sign of the unknown body is positive, the divergence of the leaves is increased; if the sign is negative, the divergence is diminished.

479. The Electric Charge Is Found on the Outside of a Conductor. Fig. 555 shows a silk bag devised by Michael Faraday. If it is electrically charged and then tested with a proof-plane, the outside *only* shows signs of the electric charge. The bag may then be turned inside out by pulling on the string A. If it is tested again for electrification, we find in this case too that the charge resides on the outside of the bag.

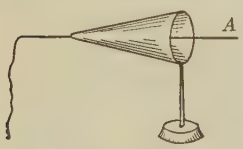


FIG. 555. — Faraday's experiment.

A hollow sphere open at the top may be used to illustrate the same fact. The electrical charge may be applied to the inside of the sphere. If we apply a proof-plane to the inside and then to an electroscope, there is no evidence of an electrical charge. When the proof-plane is applied to the outside of the hollow sphere, it will be electrified. *The electric charge always resides on the outer surface of a conductor.* This is indeed just what we might expect, if we remember that the object is charged with the same sign throughout; for like charges repel one another and take up positions on the outer surface of the conductor.

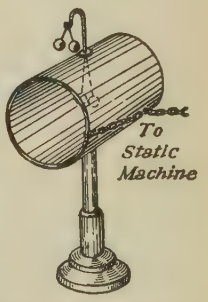


FIG. 556. — Charge resides on outside.

When a cylindrical piece of metal, insulated from the earth like that shown in Fig. 556, is connected to an electrical machine, the pith-balls on the outside repel one another, but those on the inside are not affected.

An electroscope may be protected by surrounding it with a wire screen. Then it is not influenced by any charged objects which are brought near it, since the charge spreads over the outside of the screen, and does not affect the inside.

480. The Shape of the Conductor. If we charge an egg-shaped conductor like that shown in Fig. 557 with electricity, and then test it with a proof-plane, we find that all parts are not equally charged. The density is greater at the small end than at the large. If we increase the curvature by making the surface more pointed, the density will be still more increased. *The electrical density*, or *the quantity of electricity per unit area, is greatest at the point of greatest curvature.*

481. Effect of Points. Suppose we make the egg-shaped conductor of Fig. 557 still more pointed. The density of the charge becomes so great at the point that some of the surrounding air molecules are *ionized.* Some lose electrons, and others gain electrons. Those charged with the same sign as the conductor are repelled with sufficient velocity to produce what is termed an *electrical wind.* Those air molecules that are charged with the opposite sign are attracted to the conductor, and neutralize its charge. Hence *a pointed conductor loses its charge rapidly.* Such leakage of electricity from points on the surface of a charged object is generally spoken of as the *discharging effect of points.*

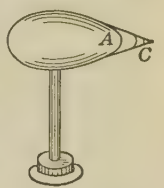


FIG. 557. — Effect of shape on intensity of charge.

A charged electroscope may be discharged rapidly by holding a needle a few inches from the knob. The point of the needle becomes electrified by induction, and discharges to the knob electricity of opposite sign which neutralizes the charge upon the knob of the electroscope.

482. Electrical Pressure. There is enough similarity between the pressure and the flow of liquids like water, and the pressure and flow of electricity that we may study

electrical units by use of water analogies. In the study of liquids, we learned that liquid pressure is directly proportional to the depth. Suppose we have an apparatus like that shown in Fig. 558. If one arm is filled with water to the level A, *pressure* is exerted against the stop-cock K. Pouring in more water increases the pressure. There is no current, however, because the stop-cock acts as *resistance*. If we remove such resistance by opening the stop-cock, water then flows from A to B until it stands at the same height in both arms of the apparatus. The pressure at A is still proportional to the depth, but it is neutralized by the back pressure at B. The rate of flow must depend upon two things: (1) The difference in pressure between the two arms; (2) The size of the opening in the stop-cock. The greater the *difference in pressure*, the faster the flow; but the larger the opening the less resistance it offers to the flow of the water. We may assume that the amount of current will be *directly* proportional to the difference of pressure, and *inversely* proportional to the resistance which the stop-cock and the friction of the pipes offer.

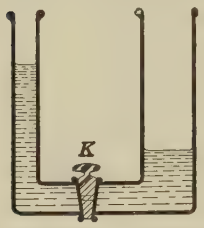


Fig. 558. — Water pressure analogy.

Suppose we have two metal balls separated by an air-gap, as in Fig. 559. If the ball A is electrically charged, pressure is exerted, analogous to the water pressure at A in Fig. 558. The more intense the charge the greater the pressure. The air-gap is an insulator, acting in the same manner as the stop-cock; hence no current flows to the ball B. If we join A and B by a copper wire, the resistance is decreased, and a current of electricity flows to B until both A and B have the same electrical pressure. Analogous to the flow of water, the strength of the current is directly proportional to the

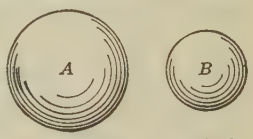


Fig. 559. — Electrical pressure.

difference of pressure between the two balls and inversely proportional to the resistance of the wire.

In *static* electricity the energy is potential; when the electrons flow through a conductor, we have an electrical *current* produced. Then the potential energy of the electrons becomes kinetic. *Electrical pressure is measured in volts.* Sometimes voltage is spoken of as *electric potential.* The earth is considered zero potential. Any object whose potential is higher than that of the earth is considered positive; if its potential is less than that of the earth, it is negative. The *available pressure is always equal to the difference of potential,* abbreviated as *P.D.* Sometimes the expression *electro-motive-force* (E.M.F.) is used to denote pressure. In formulas the letter E is used to represent the pressure in volts.

The unit of current strength used by electricians is the ampere, and the unit of resistance is the ohm. Under a pressure of one volt, a current of one ampere will flow when the resistance is one ohm.

483. Lightning. It is easy to conceive that the pressure at A in Fig. 558 might be increased to such an extent that the stop-cock would give way, or that leakage might occur. In Fig. 559, we can imagine the pressure on ball A becoming great enough to force the electricity across the air-gap to ball B. This is exactly what occurs when a spark is produced by an induction machine. When such an electrical discharge occurs, the electricity is said to "break down the insulator, or the *dielectric.*" (See Fig. 560.)

If a cloud becomes electrically charged with a higher potential than the earth, the difference of potential may be great enough to cause a violent electrical discharge between the cloud and some object on the earth. In such a case, we say the object has been "struck" by lightning. The air, which serves ordinarily as an insulator, "breaks down" under the exceedingly high voltage, and permits the dis-

charge to take place. Very often the lightning discharge occurs between two clouds that are of different potential. When Benjamin Franklin flew his kite during a storm and succeeded in drawing sparks from a key fastened to the kite string, he proved that the lightning flash and an electrical discharge are identical.

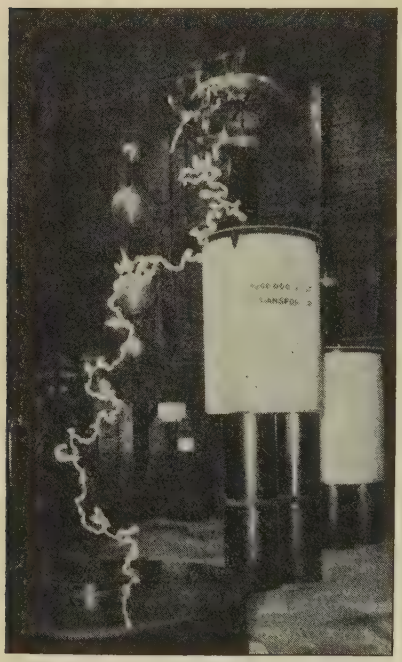


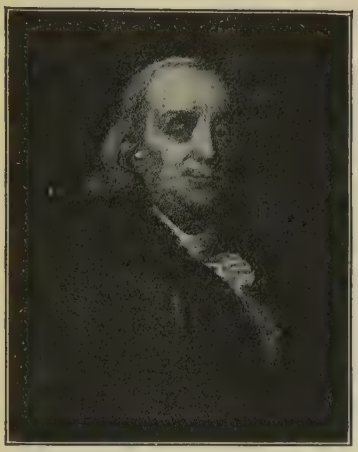
FIG. 560. — Artificial lightning produced by a million-volt transformer.

484. Lightning Rods. After Franklin had performed his well-known experiment, he invented the lightning rod for protecting buildings against lightning. A pointed rod extending above the building becomes charged inductively when a cloud passes over it, and the rod discharges the cloud quietly in much the same manner that a needle point discharges an electroscope.

The statistics of fire insurance companies show that properly installed rods are a protection, but that an improperly installed rod may be a menace. Several precautions must be taken in such installations:

1. The rod should be of a material that is a good conductor, usually copper or iron.

2. The rod must have a diameter large enough so the rod will not be melted by the current.



Benjamin Franklin (1706–1790) was an American scientist and inventor. Every school boy knows the story of the kite which Franklin flew in a thunderstorm. By means of this device he proved that lightning and electricity are identical. Franklin is the author of the "one-fluid" theory of electricity. He invented the lightning rod and the Franklin stove which replaced the old-fashioned fire-place.

Hans Christian Oersted (1777–1851) was a Danish physicist. In 1819 he made his discovery showing the connection between electricity and magnetism. He showed that a current flowing through a conductor sets up a magnetic field around the conductor. A magnetic needle brought into this field is deflected. This experiment paved the way to the discovery of the electro-magnet and the galvanometer.

3. Lightning rods should extend a short distance above the highest parts of the building, and they should terminate in several points.

4. The lower end of the rod should extend into the ground deeply enough to be always in contact with moist earth.

Opinions differ concerning the advisability of insulating the rods from the building. Both methods of installation are in use. For ordinary dwellings, it is probably better to insulate the rods to prevent lateral discharge, unless the rod runs close to a waterpipe or a gaspipe. Then they should be connected with the pipes by metal conductors. Metal roofs and gutters should all be connected and then grounded.

485. The Condenser. Let us connect the insulated metal plate A to an electroscope as shown in Fig. 561, and then apply a charge to the plate. As the intensity of the charge is increased, the leaves of the electroscope diverge more widely, showing that the potential is increased. Now let us bring *near* the charged plate a second plate B, which is connected with the earth, or grounded. The leaves of the electroscope begin to fall together as the grounded plate is brought near the first one. The quantity of electricity has not been decreased, but the potential has been lowered. Now when we continue to add electricity to the plate A, we find that the *capacity* of the plate has been decidedly increased. Several times as much electricity must be added to cause the same divergence of the leaves as before, or to produce the same potential.

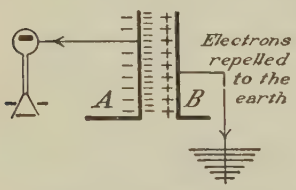


Fig. 561. — Principle of the condenser.

A combination of conducting plates separated by insulators is known as a condenser. In the example given, the air-gap serves as the insulator. If we shove a glass plate down between the two plates, the leaves collapse to some extent,

showing that the capacity is increased still more. Glass makes the insulation better. Mica is one of the best insulators for such a purpose. If we increase the size of the plates, the capacity of the condenser is increased. From our experiments, we conclude that the capacity of a condenser increases with the size of the plates, increases as the distance between the plates is decreased, and it depends upon the insulator, or the *dielectric*.

If the plate A has a negative charge, the electrons on the plate B will be repelled to the earth when the plate is brought near A, thus charging the plate B positively. The positive charge on B holds the electrons on A "bound" so that many times as many electrons can be added to A before they increase the divergence of the leaves of the electroscope to their initial value.

Fig. 562.—Leyden jar.

The *coulomb* is the unit of electrical quantity; it is the quantity of electricity transferred by a current of one ampere flowing for one second. If a condenser charged with one coulomb of electricity gives a pressure of one volt, the condenser has a capacity of *one farad*. The farad is such a large unit that the micro-farad is used as the capacity unit. It is one-millionth the value of the farad. This unit is much used in radio work.

486. Commercial Condensers. The earliest condenser is the Leyden jar, which was made at the University of Leyden, Holland, as early as the middle of the 18th century. A glass jar is coated about halfway up, inside and outside, with tin foil. A knobbed brass rod extends through the stopper; the lower end of the rod is connected to the inner surface of the jar by a brass chain. (See Fig. 562.)

To charge a Leyden jar, we connect the knob with the terminal of an electrical machine. The outer coating may be connected with the other terminal of the machine, or it may be grounded by holding the jar in the hand. In the latter case, it is connected with the earth through the human

body. Thus the charge being applied to the inner surface is held "bound" by the charge of opposite sign induced upon the outer coating. The capacity of a large Leyden jar is sufficient to give quite a severe shock when the two surfaces are touched simultaneously. The jar may be discharged in this manner or by touching the knob when the jar stands on the table. It may also be discharged by placing one end of a bent conductor in contact with the outer surface and then bringing the other end close to the knob of the Leyden jar.

Fig. 563. — Tin-foil condenser.

Condensers of the type shown in Fig. 563 are in common use. To one binding post several layers of tin foil are connected. To the other binding post we connect *alternate* layers of tin foil, all carefully insulated. For the insulation, paraffin, paraffined paper, or mica may be used. Since the two binding posts are not connected by conductors, one may be positively charged and the other negatively charged.

Variable condensers, in which the capacity may be varied, are much used in radio sets. There are several sets of stationary metal discs, having about half of the surface of the disc cut away. Similar plates of metal are mounted on an axis in such a manner that when the axis is turned, *alternate* metal plates slide between the fixed plates. (See Fig. 564.) The two sets of plates are insulated by the air, and they must not touch one another. As more of the surfaces of the plates overlap when we turn the axis, the capacity is increased. One of the dials of your radio set probably operates such a variable condenser.

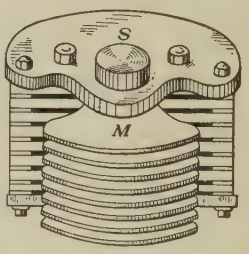


Fig. 564. — Variable condenser.

487. The Electrophorus. Volta invented the electrophorus, shown in Fig. 565. The bed *A* is composed of vulcanite

or some other insulating material. *B* is a metal disc fitted with an insulated handle. When the vulcanite bed is struck with a piece of catskin or other fur, it is negatively charged. Now if we place the disc upon the vulcanite bed, it will not be charged by contact, since it touches the surface at only a few points. *It is charged by induction.* The electrons are repelled to the upper surface of the disc, as shown in Fig. 565*A*. If we touch the disc with the finger, they are repelled to the earth. Thus the disc becomes positively charged. (See Fig. 565*B*.)

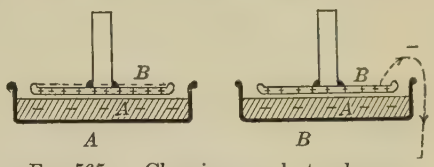


FIG. 565. — Charging an electrophorus.

If we lift the disc and hold a knuckle near the edge, a short electric spark may be drawn from the disc. By returning the disc to the bed, touching it a second time with the finger, and then lifting it, a spark may be obtained as before. This operation may be repeated several times without recharging the bed of vulcanite.

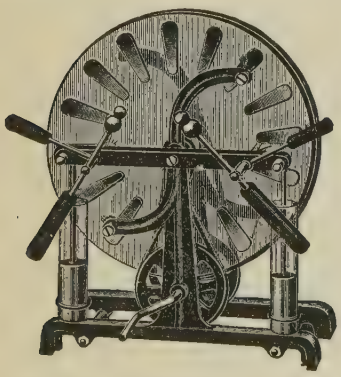


FIG. 566. — Wimshurst electrical machine.

488. Induction Machines. Several machines that generate electricity by induction have been devised. Fig. 566 shows a diagram of the Wimshurst electrical machine. When the terminals are separated, this machine builds up a very high potential difference. If the voltage or pressure becomes sufficiently high, the electrical energy will break across the air-gap, producing an electrical spark. To produce a spark only 1 cm. long requires a pressure of about 27,000 volts,

provided the terminals are rounded and not too small. If the terminals are pointed, then only about 8000 volts are required to produce a spark 1 cm. in length. To produce the lightning flash, a tremendous voltage is required. It is not uncommon to find static or induction machines which produce a spark several inches long. While the voltage is very high, yet the current which would flow continuously if the terminals were joined, is very small. Induction machines are used for demonstration purposes in the laboratory and sometimes for operating X-ray tubes.

489. Magnetism and Electricity. There are several points of resemblance between electricity and magnetism: (1) the laws of attraction and repulsion are the same in both cases; (2) either one may be produced by induction; (3) there are magnetic fields of force and electrical fields of force; (4) magnets have plus and minus poles; there are two kinds of electricity, plus and minus. Electricity is often used to produce a magnetic effect, and magnetism is very often used to produce electrical energy. The chief differences between magnetism and electricity are as follows: (1) electricity may be transmitted along a conductor, but magnetism cannot be so conducted; (2) only a few materials can be magnetized, while any substance can be electrified.

SUMMARY

Electricity may be produced in any object by friction. It may also be *induced* in an object by bringing near it a charged object.

Electricity is of two kinds, positive and negative. Like charges repel; unlike charges attract.

An electroscope is used to detect the presence of an electric charge, to determine its sign, or to measure its intensity.

Conductors transmit electricity readily; insulators, or dielectrics, are poor transmitters.

The electric charge resides on the outside of a conductor. It has its greatest density where the curvature is greatest.

The volt is the unit of electrical pressure; the unit of current strength is the ampere; the unit of resistance is the ohm.

A condenser is used to increase the capacity of a conductor. The Leyden jar is a common example. Condensers, both fixed and variable, are much used in radio sets.

Lightning is a violent electrical discharge. Metal rods are often used to protect buildings against lightning.

QUESTIONS

1. How could you electrify a metal rod?

2. Why do the leaves of a pencil pad often stick together after one has been writing rapidly for some time?

3. Why do experiments with static electricity work better on clear, dry days?

4. If the little device shown in Fig. 567 is placed on a glass plate and then connected to one terminal of a static machine, the top part whirls rapidly when the machine is in operation. Explain.

Fig. 567. —Electric whirl.

5. Why should a lightning rod end in several points? Why is a tall tree near a dwelling house an excellent protection against lightning?

6. Would a large wire screen put over a dwelling house be an efficient protection against lightning? Do you think the steel frame-work of large city buildings furnishes protection?

7. Why must a proof-plane have an insulated handle? Does a proof-plane lose all its charge when it is touched to the knob of an electroscope?

8. Compare a magnet and a charged rod, giving as many points of similarity as you can and as many differences.

9. Is attraction or repulsion the more reliable test for electrification? Explain.

10. Why is it impossible to charge a Leyden jar appreciably if it stands on an insulator?

11. When a Leyden jar is attached to each of the terminals of a static machine, the spark produced when the discharge occurs is much thickened. Explain why the Leyden jar "fattens" the spark.

12. Is the continued use of the electrophorus an example of perpetual motion? If not, what is the source of energy?

13. Place the base of a Bunsen burner against the outer coating of a charged Leyden jar. Turn on the gas and then bring the end of the burner tube near the knob. The gas will probably be lighted. Explain.

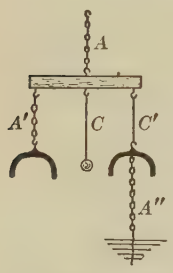


FIG. 568. — Bells.

14. Support the apparatus shown in Fig. 568 and connect it with one of the terminals of a static machine. C and C' are silk threads; A, A', and A'' are brass chains. Why do the bells ring when the machine is in operation?

15. Benjamin Franklin's experiment is a dangerous one. Explain why it should not be attempted by students.

16. Explain why both kinds of electricity are produced in equal quantity at the same time.

17. Make a series of diagrams to show how you could charge an electroscope negatively.

CHAPTER 23

ELECTRICITY—VOLTAIC CELLS

Vocabulary

Ion, an atom or group of atoms which carries an electrical charge.
Ionization, the dissociation of a chemical compound into ions.
Polarization, the accumulation of hydrogen bubbles on the positive plate of a voltaic cell.

490. Introductory. Water at rest may have potential energy, but it is not doing any work. When the water begins to flow, its energy becomes kinetic and it may do work. Frictional or static electricity is like water at rest. An electric charge at rest has potential energy, but it is not doing any work. An electric charge in motion has kinetic energy and it may do work. When an electric charge moves along a conductor, we have an *electric current.*

There is no essential difference between *static* electricity and *current* electricity. The electrons streaming along a conductor form an electric current, and the electric current may be used to charge two objects with different potentials. In order to have an electric current, we must build up a difference of potential between two points on a conductor. Then there will be an excess of electrons at one of these points, and an electric current will flow along the conductor from higher to lower potential. If the difference of potential is maintained, a *continuous current* will flow.

Suppose we have two cylinders connected near the bottom with a pipe in which a stop-cock has been fitted. (See Fig. 569.) We may fill the cylinder A with water to the line C, and the cylinder B with water to the line D. If we open the stop-cock, water will flow from A to B, but the current will

soon stop, because the level of the water will eventually become the same in both cylinders. The current will stop, because there is no *difference* of pressure. If we connect two metal balls of different potential with a conductor, the current will flow until both have the same pressure. But if we put a pump in circuit with the two cylinders of Fig. 569, we may keep pumping water from *B* into *A* fast enough to *maintain* the same difference of pressure we had in the beginning. In a similar manner, if we can keep one of the metal balls at a higher potential than the other, then a *continuous* current will flow from one ball to the other. The *dynamo* and the *voltaic cell* are used commercially to build up such a difference of potential and produce current electricity.

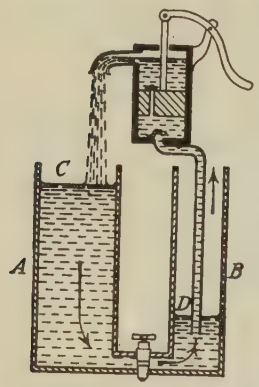
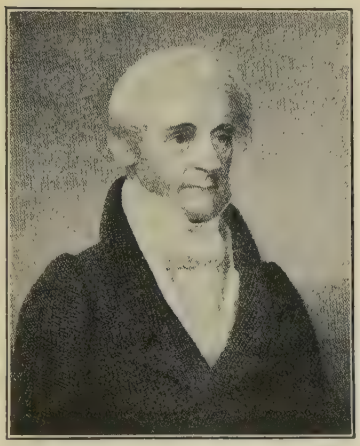


FIG. 569. — Pump maintains pressure.

491. The Voltaic Cell. In the year 1790, Galvani noticed that the muscles of a frog's leg, suspended by a copper wire, twitched convulsively when touched with a scalpel. His conclusion that the electricity lay in the nerve of the frog's leg was erroneous, but his observation led to the invention of the voltaic cell, which is usually accredited to Volta, another Italian physicist.

If we dip a zinc rod into a water solution of some acid, sulphuric acid for example, we find that bubbles of hydrogen gas are liberated by the interaction of the zinc and the acid, and that the zinc goes into solution. An electroscope test shows that the zinc is negatively charged. A carbon rod, or one made of copper, is not affected by such an acid solution, but in the presence of the zinc it acquires a positive charge. When we connect the two rods by a conductor, an electric current flows through the wire. (See Fig. 570.) The



Alessandro Volta (1745–1827) was a distinguished Italian physicist. He is the inventor of the electric battery, or the voltaic cell. His other inventions include the electrophorus, the electroscope, the electrometer, and the electrical condenser. The unit of electrical pressure, the volt, is named in his honor.

Georg Simon Ohm (1787–1854) was a German physicist. In his study of the relative conductivity of metals, he discovered the relation between voltage, resistance, and current strength. Ohm's law is fundamental in all electrical theory and measurement. In 1842 Ohm was elected Professor in the University of Munich.

chemical action of the acid on the zinc produces a difference of potential between the two rods. Since the action goes on continuously, the difference of potential between the two rods is maintained, and the current continues to flow through the wire. The voltaic cell which we have just constructed acts somewhat like the water pump of the preceding section in building up and maintaining a difference of pressure. *A voltaic cell consists of two dissimilar elements immersed in a fluid which acts chemically upon one of them.* For use in making the negative plate of a voltaic cell, no element more satisfactory than zinc has been found. Many elements have been used for the positive plate, but carbon is the most satisfactory. Copper is sometimes used. Various solutions have been used in different types of voltaic cells.

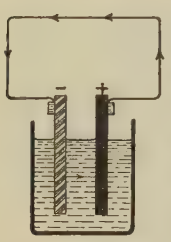


Fig. 570. — Simple voltaic cell.

492. Electrical Terms in Common Use. Each plate of a voltaic cell is fitted with a threaded bolt and nut, called a *binding post,* to which conductors may be attached. The plate that is acted upon chemically is called the *negative plate.* There is little or no action on the *positive plate.* Joining the two plates with a conductor is called "making" or "closing" the circuit. Disconnecting the conductor is called "breaking" the circuit; the cell is then on *open circuit.* A conventional diagram is used to represent a voltaic cell. In such a diagram, Fig. 571, a long, thin line represents the positive plate, and a short, thick line the negative plate. The dotted arrow between the lines represents the solution in the cell. It is customary to speak of the current as flowing from the positive plate through the *external circuit* to the negative plate. From *A* to *B* is the external circuit.

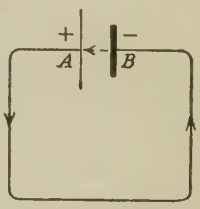


Fig. 571. — Cell on closed circuit.

In the cell the current flows from the negative to the positive plate, or from B to A. This is known as the *internal circuit.* The direction of the current *should* be changed to accord with the electron theory, but such a change would lead to considerable confusion.

493. Theory of the Action in a Voltaic Cell. For our study of the chemical action of the voltaic cell, suppose we use a cell in which the two elements, carbon and zinc, are dipped into a solution of hydrogen chloride. Such a solution is known as hydrochloric acid. The hydrogen chloride molecule is composed of one atom of hydrogen, H, and one atom of chlorine, Cl. Its chemical formula is HCl.

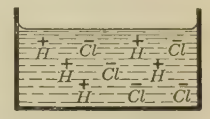


FIG. 572. — Ionization of hydrogen chloride.

According to the ionization theory proposed by Arrhenius, HCl *dissociates* in water solution into ions. *An ion may be defined as an atom or a group of atoms carrying an electric charge.* The H ion carries a plus charge and the Cl ion a negative charge, indicated as follows: H^+ and Cl^-. (See Fig. 572.) Before the strip of zinc, Zn, is put into the acid solution, it is neutral; when it is introduced, the Cl^- ions immediately begin to pull *plus* zinc ions into solution. The loss of these *plus* zinc particles leaves the zinc strip negatively charged. The excess of plus zinc ions around the zinc strip causes the plus hydrogen ions to be repelled to the neutral carbon rod. As they come in contact with the rod, their charge is neutralized; they are set free as bubbles of hydrogen gas. The H^+ ions in this way charge the carbon rod positively. (See Fig. 573.) On *open circuit* this action continues until the plus charge on the carbon exerts enough back pressure to repel the similarly charged hydrogen ions with a force equal to their repulsion by the

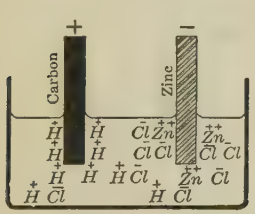


FIG. 573. — Action in voltaic cell.

zinc ions. This occurs in the case of carbon and zinc when the difference of potential is about 1.5 volts. The pressure differs with other combinations of elements. On *closed circuit* there is a fall of potential along the conductor; the chemical action going on all the time builds up a potential difference between the two elements continuously until the zinc is all dissolved or the acid spent. Therefore, *a voltaic cell transforms chemical energy into electrical energy.* (See Fig. 574.)

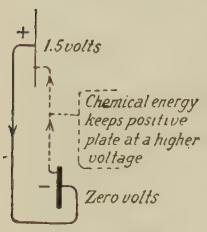


FIG. 574. — Cell builds up pressure.

494. Defects of a Voltaic Cell. There are two common defects of a voltaic cell: (1) local action; (2) polarization.

Local action. Before zinc is extracted from its ores, carbon is mixed with the ores. Hence zinc usually contains some carbon. As such commercial zinc dissolves in the acid solution of a voltaic cell, small particles of carbon are liberated. They do not dissolve, but they become positively charged and set up miniature circuits in the cell itself. (See Fig. 575.) Of course such energy does not contribute anything to the *external circuit*, and it results in wasted energy. Chemical action within the cell itself which results only in wasted energy is called *local action.*

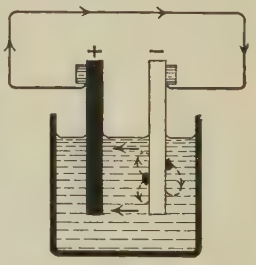


FIG. 575. — Local action.

When pure zinc is used for the negative plate, no local action occurs, but chemically pure zinc is expensive. In 1830, it was discovered that local action can be prevented if the zinc plate is amalgamated by rubbing its surface with mercury. The zinc dissolves in the mercury and is brought to the surface, but the impurities in the zinc are not dissolved; hence the carbon particles are covered up, and local action is prevented.

495. Polarization. When a voltmeter, which is an instrument used to measure electrical pressure, is connected to a cell like that described in § 491, it shows a reading of about 1.5 volts. (See Fig. 576.) If we let the cell stand for a few minutes on *closed circuit*, we find that the voltage gradually falls. The difference of pressure has not been maintained. If we examine the plates of the cell, we find that the positive plate is covered with an accumulation of bubbles of hydrogen gas. A plate of hydrogen gas has been virtually substituted for the carbon plate with which we started. The cell is said to be *polarized. Polarization, which causes the fall in voltage, is due to the accumulation of hydrogen bubbles on the positive plate.* Polarization is undesirable, since it lowers the voltage and also increases the internal resistance of the cell.

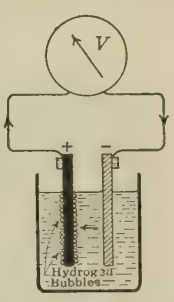


FIG. 576. — Polarization.

496. How Polarization Is Prevented or Remedied. If we lift the positive plate of a polarized cell out of the solution and wipe off the hydrogen bubbles, the voltage will return nearly to normal when the plate is put back into the liquid again. Such a remedy for polarization is neither convenient nor practicable.

If we add to the polarized cell of Fig. 576 a small crystal of potassium dichromate, or some other compound which loses its oxygen easily, the voltage rises to its original value. Potassium dichromate is an *oxidizing agent;* it gives up its oxygen, which combines with the hydrogen, forming water. Thus the hydrogen is removed and polarization is remedied by the use of some oxidizing agent. Such oxidizing agents as nitric acid, chromic acid, and manganese dioxide have been used in various types of cells to oxidize the hydrogen and prevent polarization.

Some cells have been so designed that the hydrogen bubbles

cannot reach the positive plate. Such cells are non-polarizing. Their construction will be discussed in the following section.

497. Types of Cells. Dozens of cells have been devised, differing from one another in the elements used as plates, in the solution or solutions used, and in the plan used to prevent polarization. In all of them zinc is now used as the negative plate.

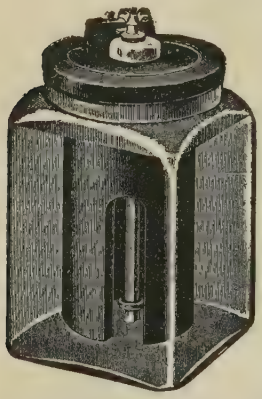


Fig. 577. — Leclanché cell.

The Leclanché cell. In the Leclanché cell, Fig. 577, the carbon and zinc plates are immersed in a saturated solution of sal ammoniac, or ammonium chloride. Manganese dioxide is generally used to oxidize the hydrogen and prevent polarization. If the circuit is kept closed for some time, the cell will polarize. It will recover again when the cell stands on open circuit, since the manganese dioxide slowly removes the accumulation of hydrogen bubbles. Such a cell is satisfactory for *intermittent* work, such as ringing door-bells.

The dry cell. Such cells differ little from the Leclanché cell. Instead of a *solution* of sal ammoniac, a *paste* of ammonium chloride, manganese dioxide, zinc chloride, powdered coke, graphite, and water is used in the dry cell. A rod of carbon is placed inside a zinc cylinder lined with pasteboard. The space between the rod and the cylinder is packed with the paste. (See Fig. 578.) The top of the cell is sealed with pitch or wax to prevent the loss of water by evaporation. The dry cell has a low internal resistance and gives a large current for *periodic* use. Like the Leclanché cell, it polarizes when used continuously, but it recovers when it stands on

Fig. 578. — Dry cell, sectional view.

open circuit. The manganese dioxide acts as a depolarizer and the zinc chloride prevents the accumulation of ammonia gas from the sal ammoniac. Dry cells are used for ringing door-bells, for operating spark-coils, for radio batteries, and for other intermittent work. The voltage is about 1.5, and the cell generally gives a maximum of about 30 amperes.

Gravity cell. In cells of this type two fluids are used. The positive plate of copper is immersed in a dense solution of copper sulphate, $CuSO_4$, which dissociates into copper ions, Cu^{++}, and sulphate ions, $SO_4^{=}$. On account of the shape of the zinc plate, this cell is sometimes called the crow-foot cell. (See Fig. 579.) The zinc is suspended in a dilute solution of sulphuric acid or a dilute solution of zinc sulphate, light enough to float on the copper sulphate solution. The zinc sulphate, $ZnSO_4$, dissociates into zinc ions, Zn^{++}, and sulphate ions, $SO^{=}_4$. In this cell copper ions, Cu^{++}, from the copper sulphate carry the positive charge to the copper plate. When their charge is there neutralized, they are deposited upon the plate as metallic copper. Thus the nature of the plate has not been changed, and the cell does not polarize. The maximum voltage of the cell is about 1.1 volts, but the internal resistance is so large that the current is generally less than 1 ampere. Such cells are used where a constant voltage is needed. Unlike most cells, they work better when kept on closed circuit.

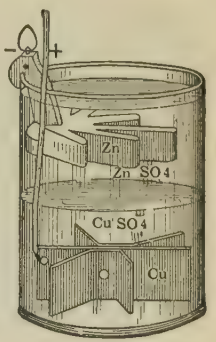


FIG. 579. — Gravity cell.

The Daniell cell. The plates and solutions of the Daniell cell are the same as those used in the gravity cell. The zinc plate is placed in a solution of zinc sulphate in a *porous* cup. (See Fig. 580.) The copper plate is bent into a cylindrical shape; it is placed around the porous cup and immersed in a solution of copper sulphate. The porous cup prevents the

mixing of the two liquids. The chemical action is the same as that of the gravity cell. The Daniell cell is non-polarizing; it gives the same voltage as the gravity cell, but its resistance is higher, and it gives less current.

498. Electrical Units Defined. We know that the *volt* is that unit of electrical pressure which causes a current of one ampere to flow through a resistance of one ohm. Unfortunately, several terms are used which have practically the same meaning as voltage. Electrical pressure, voltage, and electromotive-force (E.M.F.) are all used almost interchangeably. These terms are used just as engineers use the expression "water-head" to indicate water pressure. Potential difference (P.D.) is often used to indicate the difference in voltage between two points in an electrical circuit. The Clark cell is the legal standard for determining voltage in the United States. At 15° C. it gives 1.434 volts. The Weston cell is also widely used as a standard.

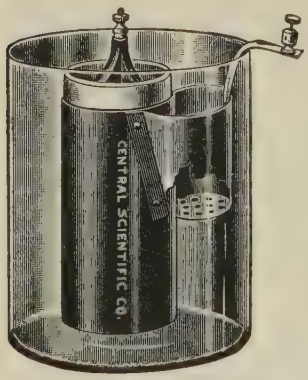


FIG. 580. — Daniell cell.

The *ampere,* which is the unit of current strength, is defined in terms of the effect it produces. When a current of one ampere flows through a solution of a silver salt, it deposits 4.025 gm. of silver per hour, or 0.001118 gm. per second. The ampere is sometimes defined in terms of the magnetic effect it produces.

The *ohm* represents the friction encountered by the electric current. It is defined as the resistance offered to the passage of an electric current by a uniform column of mercury 106.3 cm. long, cross-sectional area 1 sq. mm., at a temperature of 0° C.

499. Ohm's Law. Let us refer again to § 490. It is obvious that the amount of water that will flow from A to B depends upon the difference of pressure between the two, and upon the resistance offered by the stop-cock. It also follows that the amount of electric current flowing from A to B increases as the difference in voltage increases; the amount of current also decreases as the resistance between the two balls increases. Ohm was the first to state these observations in the form of a definite law. OHM'S LAW, which is one of the most important truths pertaining to electricity, may be stated as follows: *The current flowing in a circuit is directly proportional to the difference in pressure in volts and inversely proportional to the resistance in ohms.* Therefore,

$$\text{current (amperes)} = \frac{\text{pressure (volts)}}{\text{resistance (ohms)}}.$$

If we represent the current in amperes by the letter I, the difference in pressure by the letter E, and the resistance in ohms by the letter R, then Ohm's law may be stated algebraically as follows:

$$I = \frac{E}{R}.$$

PROBLEM. In an electrical circuit, what pressure in volts is required to cause a current of 10 amperes to flow through a resistance of 4 ohms?

Solution. Substituting in the formula, $I = \frac{E}{R}$, we have $10 = \frac{E}{4}$. Whence, $E = 40$, the pressure in volts.

500. Laws of Resistance. We have already learned that substances differ in the resistance they offer to the passage of the electric current. Some are good conductors, while others have a very high resistance. Of course the *conductance* is inversely proportional to the *resistance*. Several factors affect the resistance.

1. *Law of lengths.* We would expect 10 ft. of waterpipe to offer 10 times as much friction to a current of water flowing through the pipe as 1 ft. By analogy, we would expect that 10 ft. of wire would have 10 times as much resistance as 1 ft. Since experiment shows that this is true, we conclude that *the resistance of a conductor is directly proportional to its length.*

2. *Law of diameters.* Everyone knows that a 6-inch pipe will carry a larger current of water than a 1-inch pipe, even if the pressure is the same in both cases. The friction encountered in trying to force water through a pin-hole opening is much greater than that which must be overcome in forcing water through a larger opening. In a similar manner, a large wire offers less resistance to a stream of electrons than a small wire does. In fact, experiment shows that a wire 1 mm. in diameter has *four times* as much resistance as a wire 2 mm. in diameter, provided both have the same length. The latter wire has four times as much cross-sectional area. Hence we conclude that *the resistance of a conductor is inversely proportional to the square of the diameter, or to its cross-sectional area.* A broad street carries more traffic than a narrow one, because it offers less resistance.

3. *Effect of temperature.* More current flows through the coils of a bread toaster when the coils are cold than after they have become heated. *The resistance of a metallic conductor increases with the temperature.* Kamerlingh Onnes found that tin and lead immersed in liquid helium ($-269°$ C.) have almost no resistance. At such low temperatures they became super-conductors.

The resistance of carbon, non-metals, and the solutions of acids, bases, and salts, decreases with a rise in temperature. Glass becomes a fairly good conductor when it is heated.

4. *The resistance depends upon the material.* Copper is used more extensively as a conductor than any other metal. It offers less resistance to the passage of the current than any

other metal except silver. If we let K represent a *constant* depending upon the material, it is possible to summarize the LAWS OF RESISTANCE in the following formula:

$$R = \frac{Kl}{d^2};$$

l is the length of the conductor in feet; d is the diameter of the wire in *mils*. *A mil equals 0.001 inch.* Engineers sometimes use the term "circular mils" to represent the cross-sectional area of a wire. The circular mil equals the square of the diameter expressed in mils. A wire has a diameter of 0.025 in.; its diameter equals 25 mils; its cross-sectional area equals $(25)^2$, or 625 circular mils. The constant K expresses the resistance in ohms of one foot of wire whose diameter is 0.001 in.; it is the resistance of one mil foot of wire. The following table gives the value of K for a few of the most common conductors:

Silver	9.74	German silver	125–196
Copper	10.38	Mercury	616.5
Aluminum	17.4	Nichrome	747.4
Platinum	58.8	Manganin	251–450
Iron	64.0		

PROBLEM. Find the resistance of 150 feet of No. 24 copper wire (diameter equals 20.1 mils).

Solution. We have the following data: length equals 150 ft.; d equals 20.1 mils; and K equals 10.38. Substituting these values in the formula,

$$R = \frac{Kl}{d^2},$$

we get

$$R = \frac{10.38 \times 150}{(20.1)^2}.$$

Whence we find R, the resistance, equals 3.85 ohms.

501. The Voltage of Cells. Let us connect a voltmeter to the terminals of a non-polarizing cell. If we move the

plates of the cells nearer together, the voltage is not affected. When we lift one of the plates, the voltage is not affected as long as the plates touch the liquid. Experiment also shows that the size of the plates does not affect the voltage of the cell. In fact, experiment shows that the *voltage of a cell depends only upon the materials used in its construction.*

502. Resistance of Voltaic Cells. Let us connect a voltmeter V to the terminals of a cell as shown in Fig. 581, and then connect an ammeter A in the circuit to measure the number of amperes of current that are flowing in the circuit. If we put a coil of wire C in the circuit, the current will be decreased because the *external resistance,* R_e, has been increased. If we separate the plates more widely, the ammeter reading will be less. The *internal resistance* r_i (in the cell itself) is increased because the current must flow through a longer liquid path. For a voltaic cell we must consider both the resistance in the cell and the external resistance. Then Ohm's law becomes,

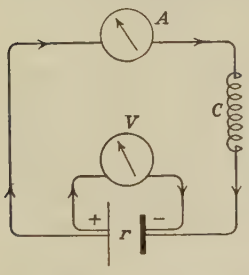


FIG. 581. — To measure resistance.

$$I = \frac{E}{r_i + R_e}.$$

If we lift the plates a little, the internal resistance is increased because the liquid path has been reduced in cross-section. While the voltage is not affected by the size or shape of the plates or the distance between them, yet the internal resistance is less when we use large plates and put them as close together as possible. The *maximum* current any cell can give equals its voltage divided by its *internal* resistance, the external resistance in such a case being zero. In making cells, the manufacturer tries to keep the internal resistance small.

The internal resistance of the various types of cells differs widely. The dry cell has an internal resistance of from 0.05 to 0.1 ohm. Since its voltage is 1.5, its maximum current varies from 15 to 30 amperes. In the gravity and Daniell cells the internal resistance usually varies from 1 to 6 ohms. Hence the maximum current such cells can furnish is usually less than 1 ampere.

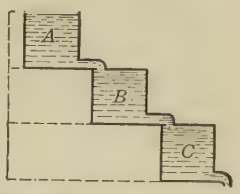


FIG. 582. — Water analogy. Series grouping.

503. Grouping of Cells. (*a*) *Series grouping.* Suppose we have three water tanks arranged one above the other, as shown in Fig. 582. It is evident that each tank adds to the water pressure by increasing the depth. In fact the pressure becomes three times as great. When we group three cells *in series* by connecting the negative terminal of one cell with the positive terminal of the next, and so on, as shown in Fig. 583, *each cell increases the electrical pressure or voltage.* If a single cell has an E.M.F. of 1.5 volts, three cells in series will have an E.M.F. of 4.5 volts. But the water must flow through each of the tanks in turn; hence it encounters three times as much resistance. In a similar manner the current must flow through each of the cells. For that reason the *internal* resistance of three cells in series is just three times that of a single cell. For series grouping of cells we must modify Ohm's law by multiplying both the voltage and the internal resistance by the number of cells, which we may represent by the letter n. Of course the external resistance is not affected by changes in cell grouping.

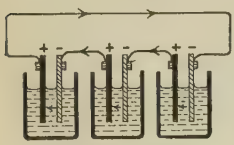


FIG. 583. — Series grouping.

Formula for series grouping, $I = \dfrac{nE}{nr_i + R_e}$.

Certain rules which apply to cells in *series* may be formulated as follows:

1. Ohm's law applies to series circuits.

2. The *voltage* across the terminals of *all* the cells in a *series* circuit is equal to the *sum* of all the separate voltages. Hence we multiply E, the voltage of a single cell, by n, the number of cells.

3. The total *resistance* of a series circuit is equal to the *sum* of all the separate resistances. Hence we multiply r_i, the resistance of a single cell, by n, the number of cells.

4. The amount of *current* is the same in every part of a *series* circuit.

(*b*) *Parallel grouping.* Suppose we have three tanks of water all at the same level, as in Fig. 584. Connecting them all to the same external pipe does not increase the pressure. Hence connecting tanks in parallel does not increase the water pressure. If we group three cells *in parallel* by joining all the positive plates with one wire and all the negative plates with another wire, as shown in Fig. 585, the *voltage is not increased.* Since one third of the water would naturally flow from each of the tanks connected in parallel, the resistance they offer would be reduced to one third that of a single tank. In an analogous manner one third of the current will flow through the liquid in each of the cells in parallel. Hence the internal resistance is reduced to one third that of a single cell, if three cells are grouped in parallel. While grouping cells in parallel does not increase the voltage, yet we may possibly get more current by such grouping because the internal resistance equals $\frac{1}{n}$ the resistance of a single cell.

FIG. 584. — Water analogy. Parallel grouping.

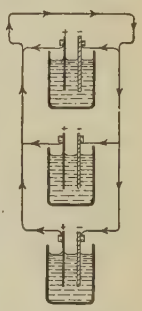


FIG. 585. — Parallel grouping.

For parallel grouping, Ohm's law may be expressed as follows:

$$I = \frac{E}{\frac{r_i}{n} + R_e}.$$

The student will find it easy to understand why parallel connections decrease resistance, if he stops to consider that more current can flow through two parallel pipes than through a single pipe. If we have two parallel roads, and one of them is closed for repairs, the traffic congestion on the other road is doubled. In an analogous manner, two parallel wires offer less resistance to the passage of the electric current than either single wire.

Certain rules which apply to cells in parallel may be formulated as follows:

1. Ohm's law applies to the entire circuit, or to any branch of the circuit:

2. The *total voltage* across the terminals of all the cells is the same as that for a single cell. Adding cells in parallel does not raise the voltage.

3. The *total internal resistance* of any number of cells in parallel is only *1-nth* of that for a single cell.

4. The *total current* furnished by the group is equal to the *sum* of the currents in all the separate parts, just as each tributary adds to the volume of water in the main stream.

504. Which Grouping Is Better? It is possible to test by laboratory experiments the methods of grouping cells. From the results of such experiments, the formulas used above were derived. By solving problems involving the methods of grouping cells, it is easy to find out which method gives the better results.

PROBLEM. Given 20 dry cells, voltage 1.5 each and internal resistance 0.1 ohm. What current will a single cell send through an external resistance of 500 ohms? What current will 20 cells give if they are grouped in series? What current will they produce if they are grouped in parallel?

Solution. (*a*) By Ohm's law we find that a single cell furnishes a current of 0.002999 ampere. $\left(\frac{1.5}{0.1+500}=0.002999.\right)$

(*b*) *Series.* Substituting the values in the formula,

$$I=\frac{nE.}{nr_i+R_e},$$

we obtain the following:

$$I=\frac{20\times1.5}{(20\times0.1)+500};$$

whence the current $=0.059$ ampere.

(*c*) *Parallel.* By substituting the same values in the formula,

$$I=\frac{E}{\frac{r_i}{n}+R_e},$$

we get the following:

$$I=\frac{1.5}{\frac{0.1}{20}+500};$$

whence $I=0.002999$ ampere. A single cell furnishes practically the same current when the external resistance is large, as the 20 cells grouped in parallel. The 20 cells when grouped in series furnish nearly 20 times as much current.

Problem. Suppose we have the same cells to be used with an external resistance of 0.005 ohm. What current will the 20 cells in series produce? What current will flow when they are joined in parallel?

Solution. The current furnished by a single cell equals

$$\frac{1.5}{0.1+0.005},$$

or 14.28 amperes. 20 cells in series will give as many amperes as

$$\frac{20\times1.5}{(20\times0.1)+0.005},$$

or 14.9 amperes. If we connect the 20 cells in parallel, the current that may be obtained equals

$$\frac{1.5}{\frac{0.1}{20}+0.005},$$

or 150 amperes. In the latter case the series grouping yields little more current than the single cell, while the parallel grouping gives more than ten times as much. In the first case the external resistance was large compared with the internal resistance; in the second case the reverse is true.

We may make this general rule to govern cell grouping. If the maximum current is desired, we always use such a combination of cells that the *external* and *total internal* resistances will be as nearly equal as possible. *When the external resistance is large, use series grouping; when the external resistance is small, use parallel grouping.*

SUMMARY

A voltaic cell consists of two dissimilar plates immersed in a solution that acts chemically upon one of them.

Local action in a voltaic cell is caused by miniature circuits set up between carbon impurities from the zinc and the zinc plate itself. It is usually remedied by amalgamating the negative plate.

Polarization is a defect in a voltaic cell due to the accumulation of hydrogen bubbles on the positive plate. The hydrogen may be destroyed by the use of an oxidizing agent; or, by the use of some mechanical device, it may be kept from coming into contact with the positive plate.

Ohm's law is fundamental; it may be stated as follows: The current in amperes flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance in ohms.

The resistance of a conductor: (1) is directly proportional to its length; (2) depends upon the material; (3) increases with the temperature in metallic conductors; and, (4) varies inversely as the square of the diameter.

The E.M.F. of a cell depends only upon the materials used in its construction; it is independent of the size or shape of the plates, or of the distance between them.

The current a cell can furnish is directly proportional to its E.M.F.; it is inversely proportional to the internal resistance. Its internal resistance is decreased by using large plates and by placing them near together.

Cells are grouped in series or parallel. Series grouping gives the best results when the external resistance is large; parallel grouping is better when the external resistance is small compared with the internal resistance.

QUESTIONS

1. Which should you use for ringing door-bells, dry cells or gravity cells? Give two reasons.

2. A telegraph line is kept on closed circuit when not in use. What type of cell is suitable for such use?

3. Make a list of the uses for which the dry cell is suitable.

4. A city is supplied with a three-foot aqueduct. It is connected to a reservoir having a capacity of one billion gallons. Do you think the number of gallons of water that flow through the aqueduct per minute would be increased by joining to it two other reservoirs having the same level and the same capacity? From your answer explain why three cells grouped in parallel give but little more current than a single cell when the external resistance is large.

5. Why should the date of manufacture be stamped on dry cells?

6. Why is the term "dry" cell a misnomer?

7. What becomes of the energy wasted in local action?

8. Upon what factors does the voltage of a voltaic cell depend? Of what factors is it independent?

9. The B-battery used for radio work is made up of a large number of small cells joined in series. How does the internal resistance of one of these cells compare with that of a standard sized cell?

10. When would you connect cells in series? When would you join cells in parallel?

PROBLEMS

(See Table 12, Appendix C, for diameters and gauge numbers.)

1. If a wire 0.02 in. in diameter has a resistance of 2.5 ohms per 100 ft., what will be the resistance of 400 ft. of wire of the same material, but 0.01 in. in diameter?

2. How is the resistance of a wire affected by doubling its length? by doubling its diameter? by halving its length? by halving its diameter? by doubling its length and halving its diameter?

3. A wire is 0.015 in. (15 mils) in diameter. It is 1000 ft. long. If it is made of German silver ($K = 181$), what is its resistance?

4. If you need a spool of wire having a resistance of 1000 ohms, how many feet of No. 30 G.S. wire, $K = 181$, and diameter = 10 mils, must be used? How many feet of copper wire of the same diameter must be used?

5. Calculate the resistance of 10 ft. of No. 24 nichrome wire, using $K = 700$.

6. A wire having a resistance of 10 ohms is to be made from manganin wire, $K = 400$. If the wire has a diameter of 10 mils, what length wire must be used? If the wire has double the diameter, what length will be needed?

7. The coils of wire used in an electric flat-iron must have a resistance of 22 ohms. Find the length of nichrome wire ($K = 700$) that must be used, if the diameter of the wire is 0.020 in.

8. A piece of wire 0.1 mm. in diameter has a resistance of 1 ohm. What will be its resistance if it is drawn through a die which reduces its diameter to 0.05 mm.?

9. A voltaic cell has an E.M.F. of 1.4 volts; its internal resistance is 0.3 ohm. What current will it furnish when the external resistance is zero? When the external resistance is 0.4 ohm?

10. How many voltaic cells would need to be connected in series to light a 110-volt incandescent lamp, if each cell has an E.M.F. of 1.5 volts? Could such a lamp be lighted by grouping such cells in parallel? Give a reason for your answer.

11. The maximum current of a Daniell cell is reduced exactly one half when a wire having a resistance of 2 ohms is connected in series with the cell. What is the internal resistance of the cell?

12. How much current will flow through the coils of a flat-iron which has a resistance of 22 ohms, if it is connected to a 110-volt circuit?

13. The amount of current flowing through the filament of a lamp is 0.22 ampere. It operates on a 110-volt circuit. What is the resistance of the hot filament?

14. How much current flows through a circuit having a resistance of 5 ohms, if the voltage is 50?

15. A voltaic cell has an E.M.F. of 2 volts; its internal resist-

ance is 0.2 ohm. Calculate the current that six such cells joined in series will yield, if the external resistance is 50 ohms.

16. What current will the six cells used in problem 15 furnish if they are grouped in parallel?

17. What current will the six cells of problem 15 furnish if they are joined in series, and the external resistance is 0.05 ohm? If they are joined in parallel with an external resistance of 0.05 ohm?

18. A voltaic cell has an E.M.F. of 1.5 volts; its resistance is 0.08 ohm. Six such cells are joined in series. What current will flow if the external circuit consists of a piece of copper wire 30 ft. long, and 15 mils in diameter?

19. Not more than 5 amperes of current must flow through a certain appliance which is to be used on a 110-volt circuit. Its resistance is 10 ohms. What resistance must be used in series with this appliance to reduce the amperage to the desired amount?

CHAPTER 24

EFFECTS OF THE ELECTRIC CURRENT

Vocabulary

Electrolysis, the decomposition of a compound by means of the electric current.

Electrolyte, a compound which ionizes when melted or dissolved and thus becomes a conductor of electricity.

Cathode (*kata*, down; *odos*, way), the negative terminal of an electrolytic cell, or the way by which the current leaves the cell.

Anode (*ana*, up; *odos*, way), the positive terminal of an electrolytic cell, or the way by which the current enters the cell.

Metallurgy, the science of extracting metals from their ores.

Sulphation, an accumulation of lead sulphate on the plates of a storage cell.

505. Introductory. We have learned that the electric current is an example of kinetic energy. Electricity in motion may produce various effects. When the electrons are pushed through a conductor, part of their energy is transformed into *heat* energy. They may even heat the conductor to incandescence and thus produce *light*. Sometimes the electric current decomposes a compound and produces a *chemical* effect. Electricity may produce *magnetic* effects, or it may act upon the muscles causing them to contract convulsively. Its effect in such a case is *physiological*.

A. MAGNETIC EFFECTS

506. Electricity in Motion Produces a Magnetic Effect. In 1819 Hans Christian Oersted, a Danish physicist, made a discovery which marked an important step in the progress of the science of electricity. He found that a current flowing through a conductor sets up a magnetic field around the conductor. He observed that a compass needle brought near

the conductor was deflected by the lines of force of such a magnetic field. While this discovery may seem rather unimportant, yet it has led to several important things: 1. It enables us to determine the direction in which a current is flowing from a study of the lines of force produced. 2. It led directly to the electro-magnet, which finds so many practical uses. 3. By the use of this principle, instruments have been devised for detecting the presence of the electric current or for measuring its strength.

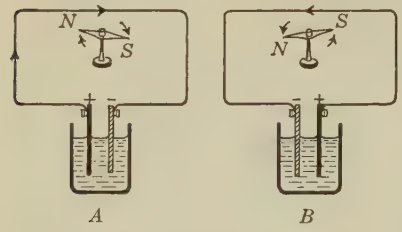


FIG. 586. — Oersted's experiment.

507. How the Direction of the Current Flow Is Determined. If we use an apparatus like that shown in Fig. 586, the magnetic needle, when placed under the wire carrying a current, will turn on its axis and tend to set itself at right angles to the conductor. Suppose we have a compass needle in a north-and-south line and a wire placed over it. When the current flows from south to north in the wire, the north-seeking pole is deflected toward the west. When the current is reversed, the north-seeking pole of the needle is deflected toward the east. (See Fig. 586, *A* and *B*.) If we get a bird's-eye view of the apparatus and look down upon it, then the deflections will appear as shown in Fig. 587.

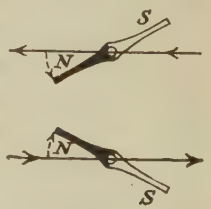


FIG. 587. — Looking down upon the needles.

Right-hand rule. (1). To aid the student in remembering the relation between the direction the current flows and the deflection of the needle, a right-hand rule has been formulated as follows: If the wire is above the needle, *hold the right hand above the wire, palm downward, with the thumb pointing in the direction the north-seeking pole of*

the needle is deflected; the extended fingers point in the direction the current is flowing.

Some students find it easier to remember the following: *If one imagines himself swimming with the electric current, facing the needle, his extended left arm points in the direction of the deflection of the north-seeking pole.* Of course, if the wire is placed below the needle, we would need to imagine the person swimming on his back.

508. Lines of Force about a Conductor. From Oersted's experiments, it is evident that an electric current produces an electrical field in which magnetic lines of force encircle the conductor. Let us pass a vertical wire through a cardboard and place thereon four small compasses. When a current flows through the wire, the compass needles are deflected until they become nearly tangent to the lines of force about the conductor. When the current flows *upward*, the lines of force encircle the conductor in a counter-clockwise direction, Fig. 588*A*. When the current flows *downward*, the lines of force are *clockwise*, Fig. 588*B*.

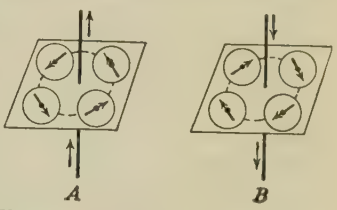


FIG. 588. — Lines of force about a conductor.

Right-hand rule. (2). Here again a right-hand rule may be used to show the relation between the direction of the current flow and the direction of the lines of force. *If we grasp the conductor with the fingers of the right hand encircling it in the direction of the lines of force, the extended thumb points in the direction in which the current flows.*

509. The Helix or Solenoid. If we make a loop in a wire carrying a current, *the faces of the loop will show polarity.* The reason for such polarity becomes obvious, if we study the direction of the lines of force about the wire. (See Fig. 589.) Inside of the loop all the lines of force are upward,

toward the north-seeking pole. On the outside of the loop all the lines of force are downward, toward the south-seeking pole. The face of the loop toward the observer becomes the *north-seeking pole* when the current flow in the loop is *counter-clockwise*. Reversing the direction of the current reverses the polarity.

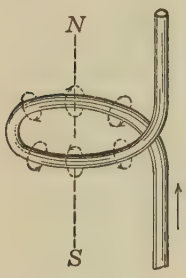


FIG. 589. — Loop of wire a disc magnet.

The polarity becomes much more pronounced, if we wind several such loops in the form of a spiral. (See Fig. 590.) Of course each loop becomes a magnet, and the whole spiral then acts like a row or pile of disc magnets with their unlike poles adjacent. Such a spiral is called a *helix* or a *solenoid*.

510. The Electro-magnet. If we refer to Fig. 590, we see that many of the lines of force tend to stray between the loops of the helix. Thus the magnetic force is scattered. To prevent such dissemination of the magnetic force, we may place an iron bar in the helix. The iron core is very permeable, and it affords an excellent path for the lines of force. (See Fig. 591.)

FIG. 590. — Helix.

Now we have an *electro-magnet*, a development from Oersted's experiment that was made practical by Joseph Henry, an American physicist.

FIG. 591. — Iron bar in helix concentrates lines of force.

If we wish to make an electro-magnet, we select a core of soft iron of great permeability. Upon this core we wind a large number of turns of *insulated* wire and then pass a current of electricity through the wire. The wire must be insulated to prevent a short-circuit from one coil to the next, or through the iron core. When the circuit is closed, the current flows through

the coils and forms a temporary magnet. When the circuit is broken, an electro-magnet loses nearly all its magnetism. The iron core retains a trace of *residual* magnetism.

511. The Strength of an Electro-magnet. There are several ways in which the strength of an electro-magnet can be varied. If we wind a larger number of turns of wire on the iron core of the preceding section, the strength of the magnet is increased. The more permeable the core the more easily it is magnetized and the more completely it is demagnetized. Increasing the strength of the current in amperes increases the strength of the magnet. To combine both statements, *the strength of an electro-magnet depends upon the number of ampere-turns.*

512. Polarity of an Electro-magnet. If we have a small compass needle, we can find the polarity of an electro-magnet by observing which pole of the magnet attracts the north-seeking pole of the compass needle. Or we may make use of the direction of the lines of force just as we did with the helix. This gives us a third right-hand rule.

Right-hand rule. (3). *Grasp the magnet with the fingers of the right hand encircling the magnet in the direction the current flows; the extended thumb points to the north-seeking pole of the magnet.* A horse-shoe magnet is so wound that the current will flow in opposite directions around each pole. Just as with the helix, the current flows in a *counter-clockwise* direction around the *north-seeking pole,* and in a *clockwise* direction around the *south-seeking* pole. (See Fig. 592.)

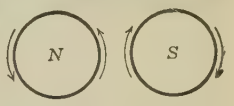


FIG. 592. — Electro-magnet. Polarity.

513. Uses of Electro-magnet. With a permanent bar magnet we can pick up a few nails, but electro-magnets can be made so strong that a load of 200 lb. can be lifted for each square inch of pole face. Such magnets are useful for loading steel billets on cars, for handling steel in steel

plants, for lifting kegs of nails, loading or unloading iron or steel scrap, and work of a similar nature. (See Fig. 593.) The surgeon uses an electro-magnet for extracting small pieces of steel from the eye-ball or other parts of the body. Many instruments and machines make use of the electro-magnet. The telegraph, the electric bell, the dynamo, and the motor are examples. Most measuring instruments make use of the electro-magnet, either directly or indirectly.

Fig. 593. — Lifting magnet. Lifting 8-ton bar of steel.

514. The Electric Bell. The action of the electric bell may be explained by reference to Fig. 594. B and D are binding posts to which the terminals of a voltaic cell may be connected. Let us suppose the current enters at D, and then trace its path through the windings back to B. The dotted lines represent wires or connections beneath the base of the bell. From D the current flows to the coils of the electro-magnet at M and M'; thence underneath the base along the dotted line to the contact screw C and the flexible spring S. This spring carries a soft iron armature to which the hammer H is attached. From S the current

flows to the binding post B through the metal base of the bell.

When the current is turned on by closing the contact key or push button, it energizes the electro-magnet, which then attracts the armature so strongly that the hammer strikes the gong G. But when the armature is pulled over toward the electro-magnet, the upper, bent end of the flexible spring S is pulled away from the contact screw at C, thus breaking the circuit. The magnet then loses its magnetism and ceases to attract the armature. On account of its elasticity the spring forces the armature and hammer back to their former position, and again makes contact at C. The circuit is now closed, and the current re-magnetizes the magnet. The whole operation is repeated as before. The spring alternately "makes" and "breaks" the circuit, and the magnet is first magnetized and then demagnetized in succession, thus causing the hammer to vibrate rapidly.

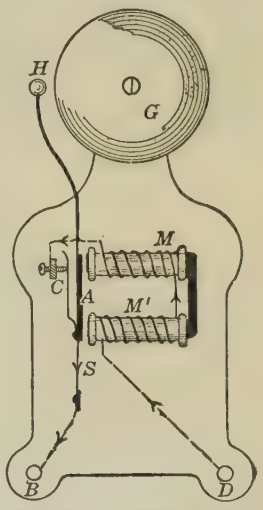


FIG. 594. — Electric bell.

Very often two or more bells are to be used with one push button; or it may happen that two push buttons are to be used with one or more bells. Fig. 595 shows that *parallel* wiring is used to secure such results. In A of this figure, if we push the button P, the current from the battery divides, part flowing through the bell B' and part through bell B''. When two push buttons are used, as in B of the same figure, the battery must be placed between the bell or bells and the *nearest* push button.

515. The Telegraph. In 1843, six years after Samuel F. B. Morse had given a public demonstration of a telegraph

operating over a half-mile of wire, Congress appropriated $30,000 to build an experimental line between Baltimore and Washington. The first message "What hath God wrought" was sent from Washington to Baltimore on May 24, 1844.

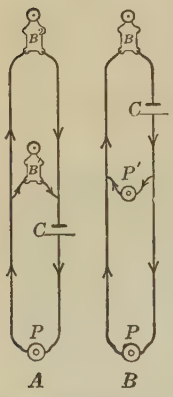


FIG. 595. — *A*. Bells in parallel. *B*. Two buttons in parallel.

For the successful operation of a telegraph system several parts and appliances are needed. The *line wires*, the *batteries*, the *key*, *the sounder*, and the *relay* are essential parts of every system.

516. The Key. The telegraph key is used merely to open and close the circuit. The apparatus is more refined than the ordinary contact key or push button, since the contact points are made of platinum or tungsten to prevent corrosion. Thus a good contact is always assured. (See Fig. 596.) When the key is not in use, a lever or switch-key S is used to close the circuit. Unless the telegraph line is kept on closed circuit, it is impossible for one operator to call another at the farther end of the line.

517. The Sounder. The word *telegraph* is derived from two Greek words meaning "end" and "write," or "end-writing." In one of the early forms a pencil was used to write the signals on a strip of paper. When the circuit of Fig. 597 is closed the magnet M attracts the iron armature A, which is carried on a lever pivoted at P, and the pencil is pulled down so that it marks the signal on a roll of paper as it is unwound from the spool. The spring S pulls the armature up away from the paper

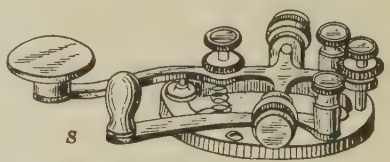


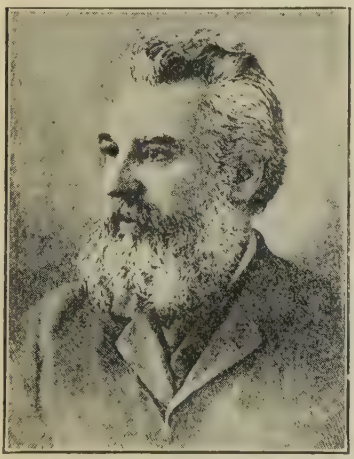
FIG. 596. — Telegraph key.

Thomas A. Edison.

Inventor of phonograph, incandescent lamp, and moving pictures.

Samuel F. B. Morse.

Inventor of the telegraph.



Alexander Graham Bell.

Inventor of the telephone.

George Westinghouse.

Inventor of air brake, electrical machines.

when the circuit is opened, and the magnet loses its magnetism.

The *sounder* is more satisfactory. It produces an audible signal. The light aluminum lever is pivoted at A, Fig. 598. It carries the iron armature I, which is pulled down by attraction when the circuit is closed through the electromagnet. As the lever is pulled down strongly, it strikes the metal D with a sharp click, thus producing the signals which the operator learns to read by sound. When the circuit is again broken, a spring at S pushes the armature back away from the magnet.

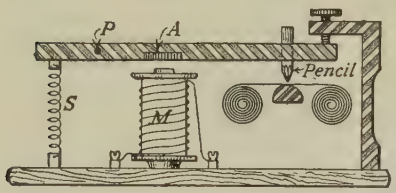


FIG. 597. — The pencil marks the "dots" and "dashes."

518. The Relay. The line wires are generally made of galvanized iron of rather low resistance. When these wires are strung on poles, they are carefully insulated to prevent grounding. Since the line is often many miles in length, the current may become so feeble that the click of the sounder is indistinct; a *relay* is then used to close a *local* circuit of which the sounder and a *local battery* form a part.

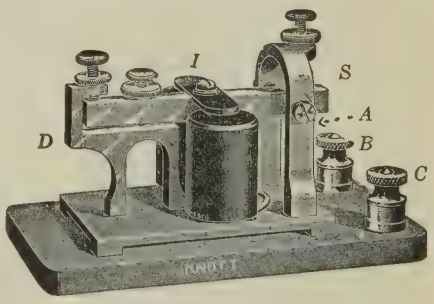


FIG. 598. — Telegraph sounder.

The *relay* is merely a circuit closer; it consists of an electromagnet with a large number of turns of wire. When the electromagnet is connected with the main line through the binding posts A and B, Fig. 599, it alternately "makes and breaks" the local circuit through the armature simultaneously

with the operation of the key. The binding posts C and D are connected in circuit with the local battery and sounder.

Fig. 600 shows how the relay, key, sounder, and batteries at one end of the line of a telegraph system are arranged. One end of the line wire is grounded at G. At B is the main line battery. When the key K is closed and the key at the other end of the line is in operation, the electro-magnet M of the relay simultaneously opens and closes the circuit through the local battery B' and sounder S. At the opposite end of the line the instruments are connected in the same manner.

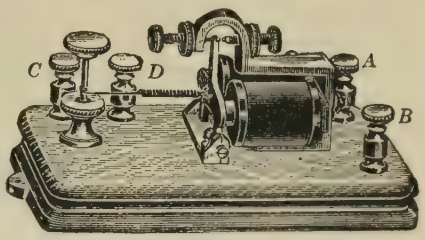


FIG. 599. — Telegraph relay.

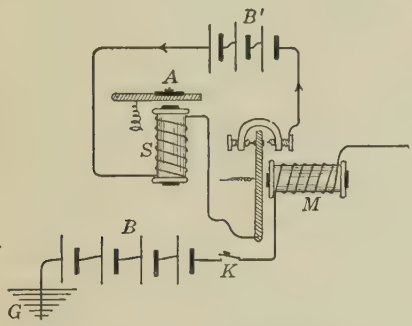


FIG. 600. — Local system, showing key, sounder, and relay.

519. The Morse Code. When a telegraph key is pressed and released quickly a short, sharp click is produced; it is known as a "dot." When the key is held for a slightly longer time, the sound is prolonged, producing what is called a "dash." Morse, the inventor of the telegraph, devised a system consisting of combinations of "dots" and "dashes" to represent the different letters of the alphabet. Formerly it was customary to use a pencil on the sounder lever, by means of which the "dots" and "dashes" were automatically recorded on a strip of paper. Operators at the present time read the message by ear from the "clicking" of the sounder.

B. CHEMICAL EFFECTS

520. Electrolysis. In § 493 we learned that the molecule of hydrogen chloride (HCl) is composed of two elements, hydrogen and chlorine. The molecule of water (H_2O) is composed of the two elements, hydrogen and oxygen. *Chemical compounds are made up of two or more elements.* Some compounds may be broken up into their elements by the action of sunlight upon them; some are decomposed by heat; and many compounds that dissolve in water or that can be melted may be decomposed by means of the *electric current. The decomposition of a compound by means of the electric current is called electrolysis.*

521. The Electrolytic Cell. The vessel or tank in which electrolysis occurs is known as an electrolytic cell. The student must distinguish between the voltaic cell and the electrolytic cell. In the former we transform chemical into electrical energy; in the latter, electrical energy is transformed into chemical energy. The voltaic cell is often called a *primary* cell, while the electrolytic cell is known as a *secondary* cell. In the electrolytic cell of Fig. 601, *A* and *B* are the *electrodes.* The electrode *A* is called the *anode.* Since it is connected to the positive terminal of some source of current, the anode is positively charged. The electrode *B* is called the *cathode.* Since the cathode is joined to the negative terminal of a dynamo or battery, it is negatively charged. Thus the current enters the cell by way of the anode and leaves by way of the cathode. The solution or liquid through which the current flows in the cell is known as the *electrolyte.*

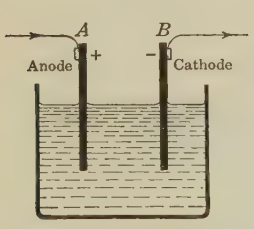


FIG. 601. — Electrolytic cell.

522. Electrolysis of Water. When we try to pass an electric current through pure water, we find that water is

not a conductor. Hence we cannot decompose it *directly* by electrolysis. An *indirect* method may be used to accomplish the same results. Let us add some sulphuric acid to the water to make it a semi-conductor. Sulphuric acid has the chemical formula H_2SO_4. When it dissolves in the water, a part of its molecules dissociate into *ions*. Each hydrogen ion (H^+) carries a positive charge of electricity, and the sulphate ion $SO_4^=$ is negatively charged. Suppose we put into such an ionized solution two electrodes of platinum or carbon and connect them to the terminals of a battery or dynamo as shown in Fig. 602. Of course the cathode will attract the hydrogen ions, since charges of unlike sign attract. For the same reason the sulphate ions are attracted to the anode.

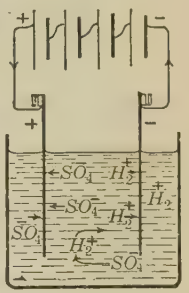


FIG. 602. — Ionization of sulphuric acid.

When the hydrogen ions reach the cathode, their charge is neutralized, and bubbles of hydrogen gas are set free. When the sulphate ions ($SO_4^=$) have their charge neutralized at the anode, they take hydrogen from the water that is present and form sulphuric acid. When the hydrogen is abstracted from water, oxygen is set free. Hence oxygen escapes at the anode, and hydrogen at the cathode. The electric current separates the ions of the acid, and the sulphate group of elements decomposes the water as shown by the following equation:

SO_4 and H_2O form H_2SO_4 and O.

Suppose we use an apparatus of the type shown in Fig. 603 for the electrolysis of water. The hydrogen accumulates in the tube that surrounds the cathode, and the oxygen in the tube that surrounds the anode. When water is thus decomposed by the electric current, two volumes of hydrogen are set free for every volume of oxygen. The amount of sulphuric acid is not changed.

A knowledge of the electrolysis of water is important for the student who wishes to understand the action of the storage cell when it is charged and discharged. Oxygen for use in oxygen helmets and hydrogen for use in filling balloons are both prepared commercially by the electrolysis of water.

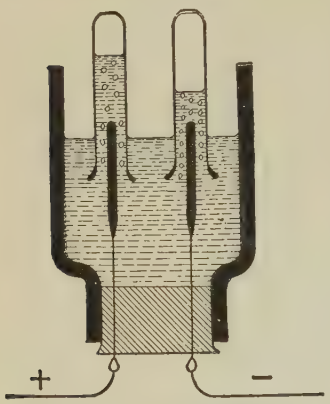


FIG. 603. — Apparatus for the electrolysis of water.

523. Electro-plating. Our most useful metal, iron, rusts rapidly when exposed to moist air. Quite often it is covered with some other metal such as nickel or chromium to protect it or to improve its appearance. Sometimes in galvanizing or in tinning, the iron is dipped into the molten metal to form such a protective covering; but frequently the metal is plated on the iron by means of the electric current. Suppose we wish to plate some metal with copper. For the electrolyte we use some salt of copper, usually copper sulphate, $CuSO_4$. The molecule of copper sulphate is made up of one atom of copper, Cu, one atom of sulphur, S, and four atoms of oxygen. When it is dissolved in water, it dissociates into plus copper ions, Cu^{++}, and minus sulphate ions, $SO_4^{=}$. The object to be plated is suspended from the cathode, as shown in Fig. 604. For the anode a bar of pure copper is used.

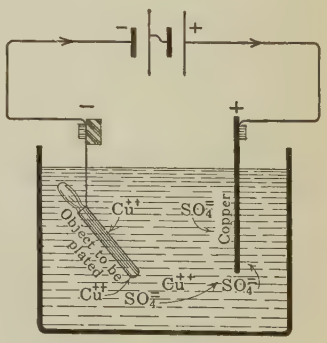


FIG. 604. — Copper plating.

When the current is turned on, the positively charged ions of copper are attracted to the cathode where they have their charge neutralized. The copper atoms do not escape, however, as the hydrogen does in the electrolysis of water, but they are deposited upon the object to be plated. The sulphate ions migrate to the anode where their charge is neutralized. They attack the copper rod used as the anode and pull more copper ions into solution. Thus the concentration of the electrolyte is kept nearly uniform.

If we wish to plate an object with silver, we attach it to the cathode, and use a bar of pure silver as the anode. Some salt of silver is used as the electrolyte. The action is similar to that which occurs during the plating with copper. The silver ions, which carry the positive charge, are deposited at the cathode.

In general, *the object to be plated is made the cathode; a bar of the pure metal with which the object is to be plated is made the anode; a salt of the metal is used as the electrolyte.* The metal plating adheres better if a relatively small current is used during the plating. When the amperage is too high, the metal plate will be crystalline, and it will scale off. More amperage may be used to hasten the process if the electrolyte is stirred or agitated. This may be done by a mechanical stirrer, or by rotating either the anode or the cathode. Thus the ions are kept evenly distributed.

524. Electro-typing. If a man wishes to print the same advertisement in a large number of magazines or papers, he may have the type set just once and electrotypes made to send to the printers. This saves labor costs, especially if the advertisement is to be repeated in successive issues. Books which are apt to pass through several successive printings are printed from electrotypes. After the type is set, an impression of each type-page is made in wax. This impression is first covered with graphite to make it a conductor, and then attached to the cathode of a copper-plating

cell. When a firm layer of copper has been deposited, it is removed and attached to some cheap metal or a wooden block to secure rigidity. From such plates or electrotypes a publisher may print a few thousand copies of a book, and then store the plates until the first printing has been sold. Phonograph records are made from one master record in a similar manner. Facsimile reproductions of chased ornaments and other works of art are often made by means of electro-typing.

525. Electro-metallurgy. In one of his lectures in a class in metallurgy, Professor Jewett, of Oberlin College, made the following remark: "Any person who discovers a proc-

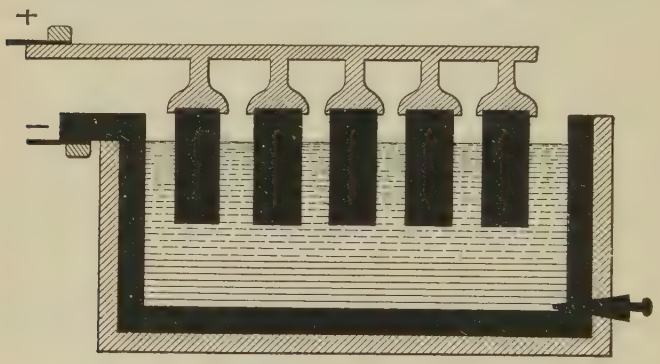


FIG. 605. — Electrolysis of aluminum oxide.

ess by which aluminum can be made on a commercial scale will bless humanity and make a fortune for himself." As the students left the room, Charles Martin Hall remarked to a class-mate—"I'm going for that metal." Two years later Hall handed Professor Jewett a lump of aluminum that he had extracted by electrolysis. The ore from which aluminum is obtained is bauxite, which consists largely of aluminum oxide, Al_2O_3. Before it can be decomposed by electrolysis, the ore must be melted to make it a conductor, or it must be dissolved in some solvent. Its melting point

is about 2000° C.; hence Hall had to look for a solvent. He found that aluminum oxide will ionize when dissolved in melted cryolite, a mineral found in Greenland. In the Hall process, the plus aluminum ions are attracted to the iron box which is made the cathode, as shown in Fig. 605. The negative oxygen ions migrate to the carbon rods which are used as the anode. Electro-metallurgy is carried on at Niagara Falls, where a cheap source of electric current is available. The Hall process was so successful that when he died in 1914, he left several million dollars, a part of the estate he acquired through his discovery, to Oberlin College.

Other metals, such as sodium, magnesium, and potassium, are *extracted* from their ores by electrolysis. Such non-metals as chlorine are also prepared by the same method. During the late war a plant at Edgewood, Maryland, had a capacity of over 100 tons of chlorine per day. The metals collect at the cathode, and the non-metals at the anode. Certain metals are also *refined* by electrolysis. Copper is purified by using a bar of impure copper as the anode, and pure copper for the cathode. As the impure copper goes into solution at the anode, pure copper is deposited on the cathode. The impurities collect in the electrolyte at the bottom of the tank. Traces of arsenic in copper lower its electrical conductivity about one half; the presence of 0.4 per cent of iron lowers its conductivity 64 per cent; therefore wire to be used for electrical purposes is made from *very pure* copper. Gold and silver are obtained from the "mud" which collects on the bottom of the tank during the refining of copper. They are separated, and then refined by electrolysis. Tin is now purified by electrolysis in American refineries.

526. Laws of Electrolysis. After one of the lectures given by Sir Humphry Davy, President of the Royal Society, Michael Faraday approached Davy and asked permission to work in his laboratory. As Davy's assistant, he discovered

how to liquefy gases, he formulated the laws of electrolysis, and later his researches led to the discovery of the principle upon which the operation of the dynamo is based. The story is told that at one time Davy was asked which of his many important discoveries he considered the greatest. His reply was "Michael Faraday."

Faraday formulated THREE LAWS OF ELECTROLYSIS. He found that a current that deposits one half pennyweight of silver in 10 minutes will deposit one pennyweight in 20 minutes. As a general statement we have:

1. *The amount of any metal that is deposited by an electric current is directly proportional to the length of time the current flows.* (Faraday's first law.)

Experiment shows that a current of one ampere will deposit by electrolysis exactly 0.001118 gm. of silver per second, and that a current of 10 amperes will deposit exactly 10 times as much per second. This determination is so exact that the ampere is defined legally in terms of the amount of silver deposited per second. Stated in general terms:

2. *The amount of metal deposited is directly proportional to the strength of the current in amperes.* (Faraday's second law.)

Some elements are deposited by electrolysis much more rapidly than others. That current which liberates 1 gm. of hydrogen can in the same time liberate 8 gm. of oxygen, 31.8 gm. of copper, or 107.88 gm. of silver.

Thus 1 gm. of hydrogen is equivalent to 8 gm. of oxygen or 9 gm. of aluminum. The third law of electrolysis may be stated as follows:

3. *The amount of an element deposited is directly proportional to the electro-chemical equivalent of the element.* (Faraday's third law.)

527. The Storage Cell. In our study of the voltaic cell, we found that two *dissimilar elements* immersed in a fluid that acts chemically upon one of them may be used to pro-

duce an *electric current*. Such a *primary* cell transforms chemical energy into electrical energy. It is also possible to start with two plates more or less *similar* and make them *dissimilar* by means of electrolysis. Thus we use the electric current *to store up chemical energy*, or to transform electrical energy into chemical energy. Such a *storage cell*, or secondary cell, may then be used just like a voltaic cell to produce an electric current. When the storage cell is *being charged*, it utilizes the electrical current. As it is *being discharged*, the stored chemical energy is utilized to produce an electric current.

528. The Lead Storage Cell. Let us immerse two lead plates in a water solution of sulphuric acid. When the two plates are connected to the terminals of a direct current dynamo or a few cells in series, the electric current decomposes the water indirectly in a manner exactly like that described in § 522. The hydrogen escapes at the cathode, but the oxygen does not escape when *lead plates* are used. (See Fig. 606.) The oxygen unites chemically with the lead anode to form lead dioxide (PbO_2). Thus the two plates are made dissimilar, since one of the lead plates has been changed at the surface into lead dioxide, a reddish brown deposit which can be seen if we look at the anode carefully. The other plate is gray and somewhat spongy.

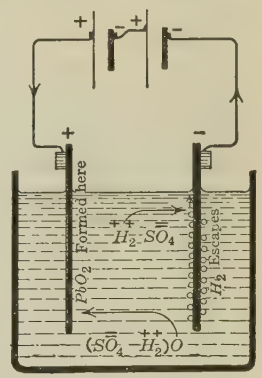


FIG. 606. — Chemistry of storage cell.

Next let us connect to a voltmeter the cell which we have just charged. It may show as high a difference of potential between the two plates as 2.2 volts. The lead dioxide plate becomes the positive plate. While the cell is discharging, the lead dioxide is being converted into lead sulphate, and

water is being formed. When the surfaces of both plates become coated with lead sulphate so that both plates are similar, no more current can flow from the cell. Fortunately the process can be reversed by charging the cell again. The equation which represents the chemical action follows:

Fig. 607. — Storage battery hydrometer.

$$2PbSO_4 + 2H_2O \underset{\text{Discharging}\leftarrow}{\overset{\text{Charging}\rightarrow}{\rightleftharpoons}} PbO_2 + Pb + 2H_2SO_4$$

The specific weight of concentrated sulphuric acid is a little more than 1.8, and that of water is 1.00. Suppose we have a cell that is fully charged. The specific weight of its electrolyte, which is a mixture of water and sulphuric acid, is 1.300. Since water is formed while a cell is being discharged (see equation) the specific weight may drop as low as 1.15. The specific weight rises again when the cell is re-charged, since water is decomposed and sulphuric acid is formed. For this reason a hydrometer like that shown in Fig. 607 may be used to determine whether a storage battery needs re-charging.

529. The Commercial Lead Storage Cell. Usually the commercial cell does not differ from the experimental cell discussed in § 528. The chemical action is the same, but the plates are more efficient. The positive plate, Fig. 608, has a large number of grids packed with lead dioxide. This distributes the active lead dioxide through the plate as well as at its surface. The negative plate has a large number of small cells or pockets filled with spongy lead to increase the amount of surface of the plate. In certain cells red oxide of lead (Pb_3O_4) is packed in the grids of the positive

FIG. 608. — Plates for lead storage cell.

plate and lead monoxide, or litharge (PbO), is used in the cells of the negative plate. When such a cell is charged, the lead monoxide is reduced to spongy lead and the red lead is oxidized to lead dioxide. Separators of rubber or wood are kept between the plates so that they may be placed very close together without touching. By the use of large plates placed close together the internal resistance is reduced to a very low figure. (See Fig. 609.)

FIG. 609. — Lead storage cell.

530. The Edison Storage Battery. Thomas A. Edison, inventor of the incandescent lamp, the phonograph, and the motion picture machine, also devised a light, strong, durable storage battery. In this cell the positive plate consists of nickel-plated, perforated

iron tubes filled with nickel flake and hydrated nickel oxide. (See Fig. 610.) The negative plate consists of nickel-plated, perforated iron cells or pockets filled with iron oxide. The electrolyte used in this cell is caustic potash (potassium hydroxide). The elements in this cell are enclosed in a strong nickel-plated iron container. (See Fig. 611.)

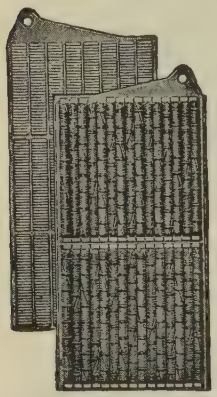


FIG. 610. — Storage cell. *A*. Negative plate. *B*. Positive plate.

531. Advantages and Disadvantages of the Storage Cell. Perhaps the greatest advantage of the storage cell lies in the fact that it may be charged and discharged over and over again almost indefinitely. Since the resistance is so small, very large currents may be obtained from storage cells. In the automobile, for example, three lead cells are generally used in series. A generator, or small dynamo, is driven by the engine. When the car is running, this generator produces current to charge the storage battery. The horn, the self-starter, the lights, and the ignition system all draw current from the storage battery.

The lead storage cell is heavy and under the best conditions its efficiency is not more than 75%. The lead cell must not be completely discharged. It is also injured by charging it too rapidly, or by drawing too large currents from it and discharging it too rapidly. When fully charged, it should show a voltage of about 2.2 and the specific weight of the electrolyte should be about 1.300. If the voltage of the cell falls below 1.8, it should be re-charged at once.

The Edison storage cell is only about half as heavy as the lead cell of equal capacity. Its efficiency is somewhat less. While the lead cell may be quite easily injured, the Edison

cell is strong mechanically, and it can hardly be injured by rapid charging or discharging. When a lead cell is discharged so completely that a hydrometer shows a reading of 1.200 or less, sulphation occurs and the cell may be permanently injured. The Edison cell is not injured even if completely

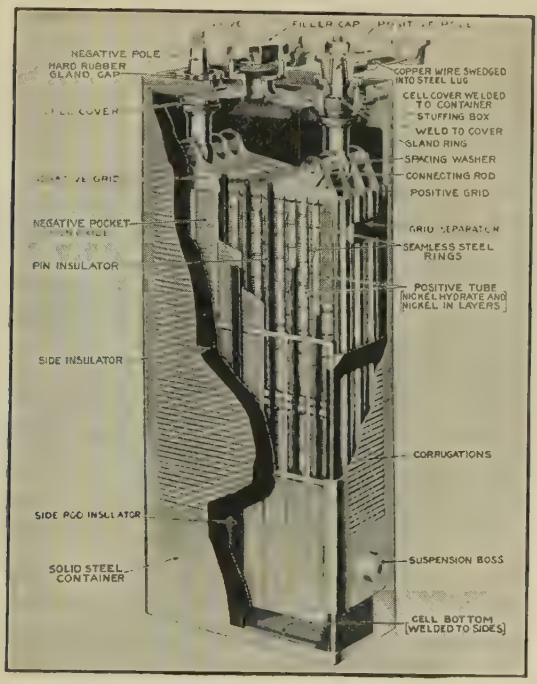


FIG. 611. — Edison storage cell.

discharged. The maximum voltage of the Edison cell is about 1.25; hence 5 Edison cells in series furnish about the same voltage as 3 lead cells in series.

532. Uses of Storage Cells. In country territory where electric current is not supplied, farmers use storage cells for lighting their houses. The cells are charged by a small

dynamo driven by a gasoline engine. (See Fig. 612.) Storage cells are also used for telephone work. In power stations they are used when the load is very light, or to help the dynamos when the load is heavy. The electric-clock systems in school buildings are operated by storage cells. If your radio set is not fitted to operate on a lighting circuit, it

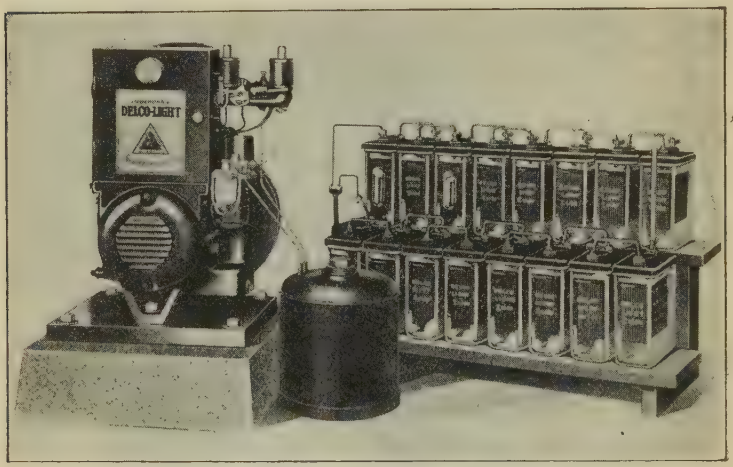


Fig. 612. — Delco-lighting unit used where electric service is not available. Storage cells and charging unit.

probably uses a storage battery for the A-battery. The use of the storage battery in automobiles is well known to all.

533. How to Care for a Storage Battery. The storage cell must not be short-circuited or used with too low a resistance. Distilled water must be added to replace the water that is lost during the operation of the cell. Batteries should be tested either with a voltmeter or a hydrometer. If the charge is too low, they should be re-charged at once. If a storage battery is not to be used for a period of a few months it should be fully charged before it is laid aside.

C. HEATING EFFECTS

534. Heating Effects of the Electric Current. Let us connect two binding posts to the terminals of a dry cell, as shown in Fig. 613. We shall first join the two binding posts by two short wires connected in series. Both should be of gauge No. 30. One is made of copper and the other of German silver. When the circuit is closed through the contact key K, the German silver wire will be heated red hot and it may melt. The copper wire will also be warmed. From this experiment, we learn that *the heating effects of an electric current are greater in the wire which has the greater resistance,* if other conditions are the same. Such a result might have been predicted, because we know that resistance or friction produces heat energy. The wires leading to our electric lights are not warmed very much because the current flowing through them is not very great, and their resistance is small; but the filament in the bulb of the incandescent lamp is heated white hot by the same current. The filament generally has a resistance of 100 or more ohms.

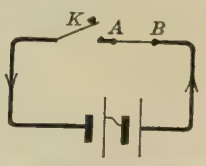


FIG. 613. — Heating effect of current.

Let us repeat the experiment, using a few inches of No. 28 copper wire to connect the binding posts. When the current from a single cell is passed through such a wire, it may glow. If the current from two or three cells in series is used, the copper wire may be melted. *We find that the heating effect increases with an increase in the number of amperes flowing in the circuit.*

535. Joule's Laws. It was James Prescott Joule, an English physicist, who first studied the relationship between heat and work. He was also the pioneer in the study of the heating effects of the electric current in a mathematical way. He carried out a series of experiments and formulated several

laws that enable us to determine quantitatively the amount of heat developed in a conductor when a current is flowing through it. His statements are known as JOULE'S LAWS:

1. *The amount of heat is directly proportional to the resistance in ohms.*

2. *The amount of heat is directly proportional to the square of the current in amperes.*

3. *The amount of heat is directly proportional to the time the current flows.*

If the amount of heat produced is to be expressed in *calories*, the product of the square of the current in amperes times the resistance in ohms times the time t in seconds must be multiplied by the constant quantity 0.24. As a formula,

$$\text{calories} = I^2R \times t \times 0.24.$$

PROBLEM. The heating coil in a coffee percolator has a resistance of 22 ohms and uses 5 amperes of current. How long will it take to heat one liter of water from 20° C. to the boiling point, 100° C., in such a percolator?

Solution. To heat one liter of water (1000 gm.) from 20° C. to 100° C. requires 80,000 calories. Substituting the values in the formula,

$$\text{calories} = I^2R \times t \times 0.24,$$

we have

$$80{,}000 = 5 \times 5 \times 22 \times t \times 0.24;$$

whence t equals 606 seconds, just a trifle more than ten minutes.

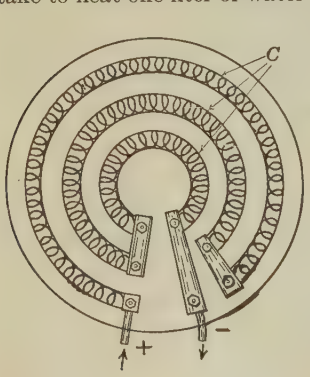


FIG. 614. — Electric heater. (Coils of nichrome wire.)

536. Applications. The *electric flat-iron*, the *bread-toaster*, the *coffee percolator*, the *electric grill*, and the *electric heater*, Fig. 614, are all familiar applications of the heating effects of the electric current. Many trolley cars are now heated by electric heaters. In

each of these cases coils of high resistance wire, often made of nickel or nichrome, are so grouped that a great deal of heat is concentrated at one place. (See diagram of the heating coil in an electric flat-iron, Fig. 615.) Electric cooking and heating are expensive at the price usually charged to small consumers. In some localities a lower rate is made where current is to be used for heating or for operating power motors.

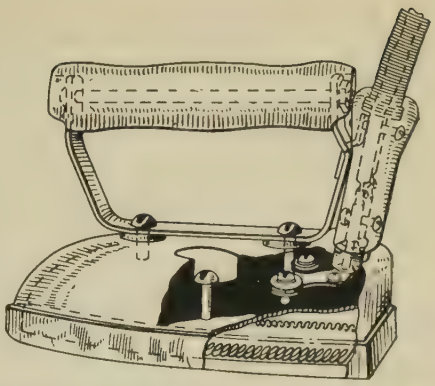


FIG. 615. — Electric flat-iron. Cut away to show heating coils.

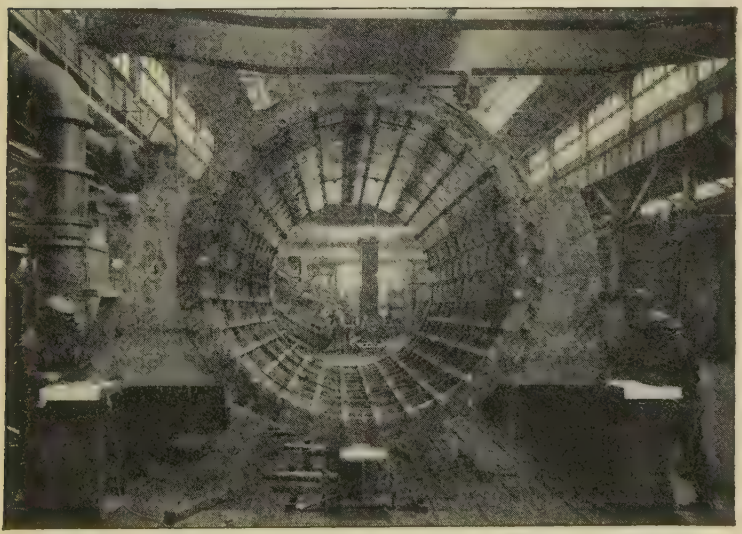


FIG. 616. — Electric welders and large stator electrically welded.

If two pieces of wire are placed end to end and a current is passed through them, the heat developed at the point of contact is sufficient to *weld* them into one piece. Electric welding is extensively used by trolley companies. The edges of metal plates are sometimes welded electrically instead of being riveted together. (See Fig. 616.)

537. Overloading Wires. In § 534 we found that the current from a couple of dry cells in series would melt No. 30 copper wire readily. If we send the same current through a piece of wire of the diameter used for wiring dwellings (No. 14), the wire will become hot, but it is not apt to melt. The larger wire has a greater carrying *capacity*. It can *carry more amperes safely*. The carrying capacity of a bare wire is greater than that of an insulated wire of the same diameter, and a wire around which air circulates freely can carry safely more current than a like wire that is enclosed. If we try to force more current through a wire than it can *safely* carry, we have an *overload*. Such a wire may melt, and it may set fire to flammable material that is near it. An overload may be caused by putting too many electrical appliances on one circuit, or it may be caused by a *short-circuit*. Suppose we have an incandescent lamp which has a resistance of 500 ohms. It operates on a 110 volt circuit. The current that flows through the lamp is 0.22 ampere. (Ohm's law.) If we remove the insulation from the wires and join them by a heavy piece of wire as shown in Fig. 617, we have a short-circuit. The resistance would suddenly be reduced to less than one ohm. For comparison of the heating effects let us suppose that the resistance in the second case is exactly one ohm. The current would rise to 110 amperes. Let us compare the heating effects for the second case with those of the first.

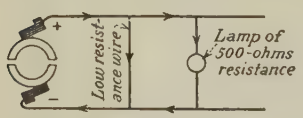


FIG. 617. — Most of the current flows through the low resistance.

$$\frac{I^2R}{I^2R}, \text{ or } \frac{110\times110\times1}{0.22\times0.22\times500}=500.$$

Hence in this example the amount of heat produced when the wires are short-circuited is 500 times as much as before. Naturally the wires would melt. Such a short-circuit might be produced by the wires being brought into accidental contact during a fire or a storm.

538. How Fuse Wires Protect Us. In the preceding section we learned that an overload may cause a fire. Even if it did not set fire to our house, the wires might melt *at any place* within the walls or ceiling. It would be troublesome to locate the break in the circuit and expensive to make the repairs. To prevent such an occurrence, *fuse wires* are used in all wiring circuits. In dwelling houses, the fuses are placed in metal boxes, Fig. 618, usually installed in the basement. Sometimes a cartridge fuse, as shown in Fig. 619, is used in certain circuits; but the plug fuse of Fig. 620 is more common. When an overload occurs, the fuse melts and breaks the circuit. It is a simple matter to replace the fuse after the cause of the overload has been removed.

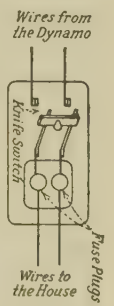


FIG. 618. — Fuses and knife switch.

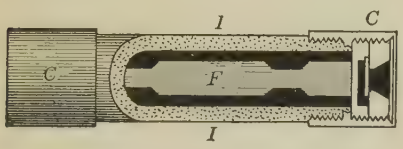


FIG. 619. — Cartridge fuse. Brass contacts are shown at *C*. The fusible metal *F* is enclosed in insulating material.

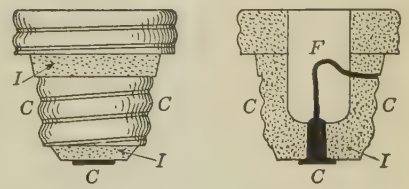


FIG. 620. — Plug fuses. The fusible wire *F* is surrounded by fire-proof material *I*.

When the electrician wires a house, he plans for a certain number of lights and appliances for each circuit. Then he

installs a fuse that has *less* carrying capacity than the wires themselves. Suppose the wires have a carrying capacity of 17 amperes. A 10- or 15-ampere fuse will melt more readily than the wire itself. A 25-ampere fuse plug is no protection for such wires.

539. Incandescent Lamps. In 1879, Thomas A. Edison first exhibited an incandescent light in his laboratory at Menlo Park, New Jersey. He had tried almost every kind of fiber in an effort to find a filament which would not melt when heated to incandescence by means of the electric current. Of course the filament had to have a high resistance; it could not be too brittle; its melting point had to be very high; it was placed in a vacuum bulb so that it would not burn, or unite with the oxygen in the air. The filament which he first used successfully was made of carbon obtained by heating bamboo fiber. (See Fig. 621.) The ends of the filament were connected to two short pieces of platinum wire P and P'. The other ends of these platinum wires were connected by copper wires, one of them to a brass disc B, which makes contact with one terminal in the lighting circuit, and the other to a threaded cylinder C, which makes connection with the other terminal of the lighting circuit when the lamp is screwed into the socket. These lamps were first used for lighting at Roselle Park, New Jersey. Such carbon filament lamps soon began to be used extensively. Now they have become practically obsolete. A 16-candle power lamp of this type operating on a 110-volt circuit needs about 0.5 ampere of current, or 55 watts. That is approximately 3.4 watts per candle. The modern tungsten lamp uses from 1 to 1.25 watts per candle.

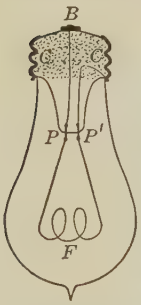


FIG. 621. — Diagram of carbon lamp.

540. Tungsten Lamps. Many efforts were made to find a more satisfactory material than carbon for use in making

the filament of incandescent lamps. The metal *tungsten* is now used almost exclusively. Tungsten has a high melting point, and a high resistance. It evaporates very slowly, even at a high temperature. The modern tungsten lamp is shown diagrammatically in Fig. 622. The filament is not coiled, but it is looped back and forth over the ends of bent wires known as anchors. An alloy consisting largely of nickel and iron has been found to take the place of the expensive platinum which had been used for lead-in wires. The bulb is frosted on the inside to prevent the glare from the hot filament.

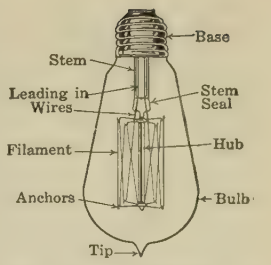


Fig. 622. — Diagram of tungsten lamp.

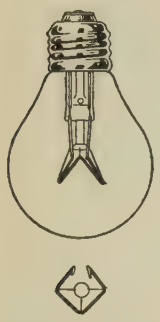


Fig. 623. — Gas-filled lamp and filament.

The light from a tungsten lamp is whiter than that from the old carbon lamp, and the efficiency is about 2.5 times as great. It shows more yellow, however, than sunlight, and it cannot be used for matching colors. The so-called daylight lamp used for this purpose has some blue in the glass from which the bulb is made.

The gas-filled lamp is a tungsten lamp in which nitrogen or argon is used for filling the bulb, Fig. 623. The long filament is wound in a very close spiral, thus preventing loss of heat by radiation. Since the tungsten does not evaporate so rapidly when surrounded by the argon-nitrogen mixture as in a vacuum, the filament can be heated to a higher temperature. The efficiency of the lamp is thus increased, and the bulb does not darken so rapidly.

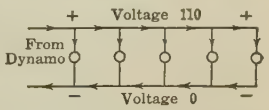


Fig. 624. — Incandescent lamps are wired in parallel.

The large-sized gas-filled lamps may need only 0.6 watt per candle power of light. The smaller ones take about 1 watt per candle. Incandescent lamps are generally grouped in parallel. The voltage between the terminals is constant. (See Fig. 624.) Each lamp is thus independent of all the others. If each lamp takes one ampere of current, then each lamp that is turned on increases the amount of current flowing in the main circuit by one ampere.

541. Arc Lighting. If two carbon rods connected to electrical terminals having a difference of potential of about 50 volts are brought together momentarily, the heat produced at the point of contact is great enough to vaporize some of the carbon and produce an intensely bright light. When the carbon rods are then separated about a quarter of an inch, the carbon vapor continues to conduct the current from one rod to the other. (See Fig. 625.) The light is produced by the luminous carbon vapor which forms the arc. A clutch mechanism is used to feed the upper arc gradually and regulate the distance between the carbon rods. This clutch is controlled by an electro-magnet.

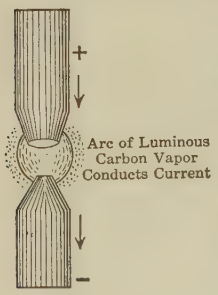


Fig. 625. — Arc lamp carbons.

The arc lamp uses from 10 to 25 amperes, varying with the diameter of the carbons. Its efficiency is a little higher than that of the vacuum type incandescent lamp, but less than that of the large gas-filled lamp. Except in large halls and rooms, arc lamps are not much used for interior lighting. They are used for street lighting and park illumination. Arc lamps are generally wired in series, about 40 lamps to a 2200 volt dynamo. (See Fig. 626.)

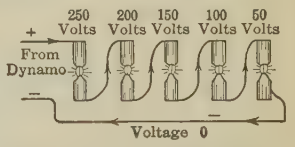


Fig. 626. — Arc lamps are wired in series.

The *flaming arc* is extensively used for park illumination. The carbons have a core consisting of the salts of certain metals, especially those of calcium and magnesium; the arc is colored by their flame and much more light is produced. They may be nearly four times as efficient as the ordinary arc lamp.

542. The Neon Lamp. For advertising display signs, neon tubes are being extensively used. Neon gas is found in small quantity in the atmosphere. This rarefied gas is put in a glass tube of any shape or design. An orange-reddish light of great intensity is produced if current is applied

FIG. 627. — Mercury vapor lamp.

to the electrodes sealed in the ends of the tubes. The cost of operating neon lamps is very small, since the current consumption is only a few thousandths of an ampere. Since the whole tube is filled with light, the effect is striking. (See Fig. 511.) Several other gases, such as helium, are used to give different colors.

543. The Mercury Vapor Lamp. The Cooper-Hewitt mercury vapor lamp is extensively used by photographers and in drafting rooms. It consists of a glass tube about 3 or 4 ft. long. The electrodes are sealed in the ends of the tube. The lamp is suspended so that the tube is slightly inclined, and the lower end contains mercury. (See Fig. 627.) If the tube is tipped so that a thin column of mercury makes contact momentarily between the electrodes, an arc is established. The heat causes the tube to be filled with mercury vapor, which

is heated to luminosity. This lamp is efficient, but it is deficient in red rays. Sometimes neon tubes are used in conjunction with mercury vapor lamps to supply the red and orange rays.

The mercury vapor lamp is rich in ultra-violet rays. These rays do not pass through glass readily, but they do pass through quartz. A mercury vapor lamp made out of quartz is useful for sterilizers, since ultra-violet rays destroy bacteria. (See Fig. 628.)

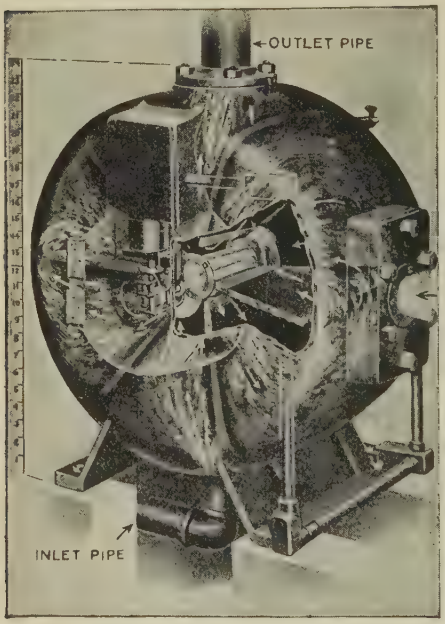


FIG. 628. — Phantom view of a water sterilizer.

544. Electric Furnaces. In the manufacture of many products the very high temperature that can be produced by means of an electric furnace is utilized. In one type of electric furnace the current of electricity passes through a coil of platinum, tungsten, nichrome, or molybdenum wire which is wound around some refractory material. The object to be heated is placed inside the coil. In such *resistance* furnaces a temperature of from 1000° C. to nearly 2000° C. can be obtained.

In the *arc type* of electric furnace a temperature of about 3500° C. may be obtained. In this furnace the electric arc is produced inside a crucible to melt the contents. (See

Fig. 629.) Electric furnaces of the arc type are used in the manufacture of carborundum, calcium carbide, artificial

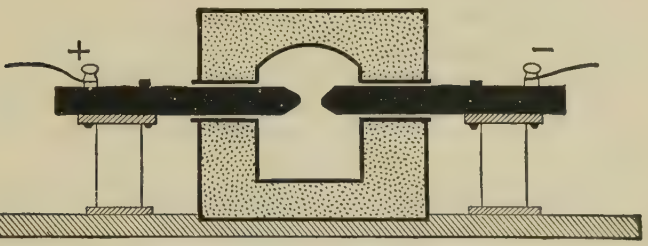


Fig. 629. — A simple electric furnace.

graphite, nitrogen compounds from the air, and high-grade steel.

SUMMARY

An electric current produces a magnetic effect. If we grasp the conductor, with the fingers of the right hand encircling it in the direction of the lines of force, the extended thumb points in the direction of the current flow.

An electro-magnet consists of a soft iron core wound with a number of turns of insulated wire. The strength of the electro-magnet depends upon the number of ampere-turns.

Electrolysis is the decomposition of a compound by means of an electric current. The current enters an electrolytic cell by the anode and leaves by the cathode. Hydrogen and most metals are electro-positive; they are attracted to the cathode. The non-metals, which are electro-negative, are attracted to the anode.

The ordinary storage cell consists of two lead plates immersed in a solution of sulphuric acid. They become dissimilar when an electric current is passed through the cell; two dissimilar plates immersed in an electrolyte produce a difference of potential. No electricity is stored in a storage cell.

An electric current produces a heating effect. The amount of heat produced is proportional to the time, the resistance, and the square of the current strength. Electric lighting is merely a modified application of the heating effects of the electric current.

QUESTIONS

1. If a helix is supported so it is free to rotate, what position does it assume when a current is passed through it?

2. How could you tell what direction a current is flowing through a wire in the ceiling of a room? If the ends of the wires are exposed, how can you tell which is the positive terminal by dipping the wires into a solution of copper sulphate?

3. Why is an iron core used in an electro-magnet? Would steel do as well? Give two reasons for your answer.

4. What is triple-plated silverware? What does the mark "12 Dwt." mean as used so frequently on silver-plated ware?

5. Draw a diagram to show an apparatus that might be used for plating an object with gold. Label your diagram carefully.

6. In what two ways can one find the polarity of an electro-magnet?

7. What is actually stored in a storage battery?

8. What is meant by the "carrying capacity" of a conductor? What does the expression "overload" mean?

9. How can Faraday's second law be used in determining the strength of an electric current?

10. What is meant by a "short circuit"? In what way is a "short circuit" dangerous? How are fuses used to eliminate such a danger?

11. Would you use a 25-ampere fuse plug with a wire which can carry safely only 17 amperes? Explain fully.

12. In what two ways may the wiring of a flat-iron be varied to concentrate the heat at the point? What is the advantage of a "hot-point" flat-iron?

13. How much is the heat in a circuit increased if the resistance is doubled and the amount of current is unchanged? How much is the heat increased if the current is doubled and the resistance is unchanged?

14. Explain why the wires leading to an electric bulb do not become so highly heated as the filament itself, since the same amount of current may flow in each.

15. Make a list of the things to be done in taking care of a storage battery for a radio set.

16. Why must an electro-plater be familiar with Faraday's laws of electrolysis?

17. A storage cell charged to its maximum capacity has a pressure of 2.2 volts. Can a single dry cell, E.M.F. equals 1.5 volts, be used to charge this cell? Can it be charged by two such cells in series? How many cells in parallel grouping would be required?

PROBLEMS

1. How much silver will a current of one ampere deposit in 15 min.? How much copper will the same current deposit in the same time?

2. If the resistance of a lamp is 220 ohms and the current flowing through the lamp is 0.5 ampere, how many calories of heat will be produced in 10 minutes?

3. A lamp operates on a 110-volt circuit. Its resistance is 550 ohms. How many calories of heat will be developed in 30 minutes? How many grams of water at 20° C. could be warmed to 80° C. by the heat that is set free by the lamp?

4. A coil of wire has a resistance of 22 ohms. If it is connected with a 110-volt circuit, how many grams of ice could be melted by the heat which the coil would set free in 10 minutes?

5. A 3-Kgm. flat-iron uses 4.5 amperes of current when operating on a 110-volt circuit. How long will it take to heat the flat-iron from 20° C. to 200° C., if there is no loss of heat by radiation? The sp. ht. of iron is 0.113.

6. A coffee percolator has a heating coil that has a resistance of 20 ohms. If it operates on a 110-volt circuit, how many calories of heat does it liberate per second? How would the amount of heat per second be affected if the coil were connected to a 120-volt circuit?

CHAPTER 25

MEASURING INSTRUMENTS

A. MEASURING INSTRUMENTS

Vocabulary

Kilowatt-hour, 1000 volt-amperes for one hour.
Galvanometer, an instrument for detecting the presence of an electrical current or for measuring its strength.
Rheostat, high-resistance coils used for introducing resistance into a circuit or for measuring resistance.
Shunt, either branch of a divided circuit.

545. The Galvanoscope. In § 506 we learned of Oersted's discovery that a current flowing through a wire sets up a magnetic field around the wire. If we wind the wire into the form of a loop and place a magnetized needle in its center, the needle will be deflected when the current flows. (See Fig. 630.) Increasing the number of turns in the coil increases the deflection. By the use of a large number of turns, even a feeble current will cause a marked deflection of the needle. Hence the deflection of a magnetic needle may be used to show that a current is flowing in the loop. Such a device is called a *galvanoscope.* (See Fig. 631.) It may be used to *detect the presence of a current* or *to determine its direction.*

FIG. 630. — Current flowing through loop affects needle.

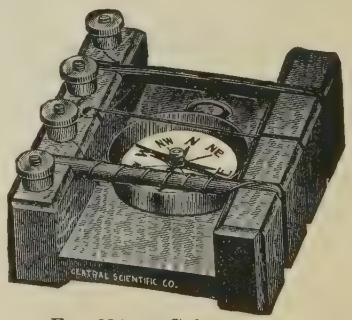


FIG. 631. — Galvanoscope.

546. The Galvanometer. *Movable-needle type.* It is not always sufficient to detect the presence of an electric current or to determine its direction. We quite often need to *measure the strength* of such a current or to find its voltage. It is possible to use a sensitive needle in the center of a coil, and to determine the strength of the current flowing in the coil by measuring the amount of deflection. Fig. 632 shows a *tangent galvanometer* that may be graduated to show the strength of the current from the amount of deflection of the *movable needle.* If a circular coil of three turns of 10 cm. radius is used, a deflection of about 45° in a small compass needle placed in the center of the coil will be caused when a *current of one ampere* flows through the coil. When the plane of the coils is in the earth's magnetic meridian, the strength of the current is directly proportional to the tangent of the angle of deflection. The angle must be kept fairly small. If a current I of 2 amperes causes a deflection of 15° and a current I' of unknown strength produces a deflection of 20°, then the strength of the unknown current may be found as follows:

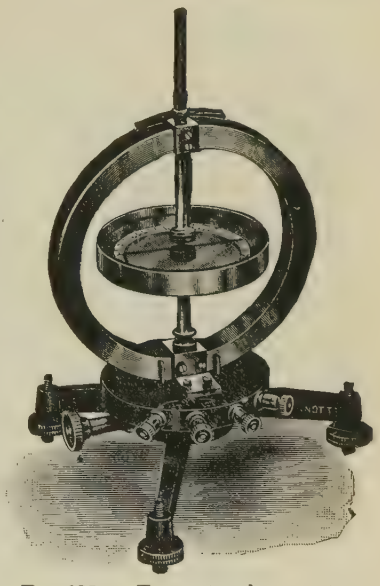


Fig. 632. — Tangent galvanometer.

$$I : I' = \tan \angle 15° : \tan \angle 20°.$$

From the table of tangents, Appendix C, we see that the two currents have the ratios 0.2679 and 0.3640, or 1 to 1.36. Hence the strength of the unknown current is 2.72 amperes.

Movable-coil type. In this galvanometer a coil is pivoted between the poles of a permanent horseshoe magnet. This coil, which is really a helix, is magnetized when a current flows through it. Thus the faces of the helix acquire polarity, and they are repelled by the poles of the horseshoe magnet. The electro-magnet is free to turn, but the horseshoe magnet is fixed. The coil, as it turns on its axis, carries a small light pointer which moves over a graduated scale. Increasing the strength of the current flowing through the coil increases the amount of magnetism and also the amount of deflection. A coiled spring causes the movable coil to return to its original position with the pointer at zero when the circuit is broken. Fig. 633 shows a movable-coil type of galvanometer. Sometimes a small mirror is fastened to the coil. A beam of light reflected by this mirror as the coil moves even a small amount falls upon a long scale placed several feet distant, thus magnifying the amount of deflection.

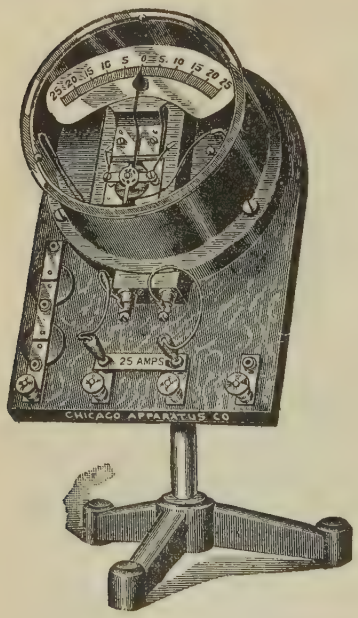


Fig. 633.—Movable coil galvanometer.

547. The Voltmeter and Ammeter. Many *voltmeters* and *ammeters* are really galvanometers of the movable-coil type. The coil is mounted on jeweled bearings to reduce the friction to a minimum. The current enters through two springs which hold the coil in such a position that the pointer stands at zero when no current flows. (See Fig. 634.) The *volt-*

meter is so graduated that it reads volts directly. The *ammeter* is graduated to read amperes.

The voltmeter coil consists of fine insulated wire wound on a light frame called a *former*. This movable coil is connected in series with a coil of *high resistance* in order to keep the difference of potential between the binding posts of the

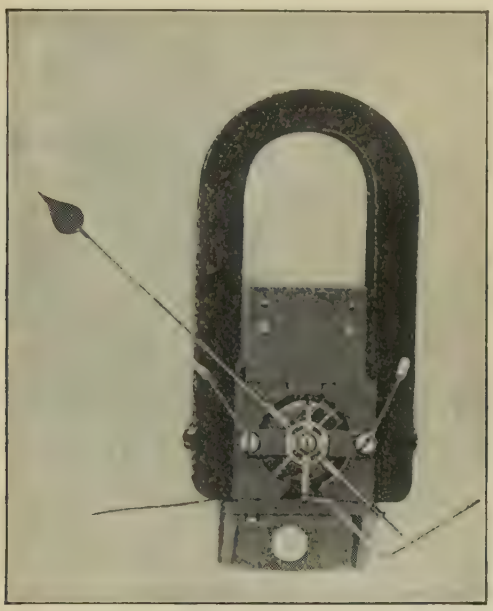


Fig. 634. — Magnet and movable coil of voltmeter.

instruments as great as possible. (See Fig. 635.) The voltmeter is used to measure the *difference of potential* between two points in a circuit. Hence it must use just enough current to cause a deflection of the needle, but not enough to lower the difference of potential. *All voltmeters are high-resistance instruments.* They are connected *in parallel* in a circuit. (See Fig. 636.)

The *ammeter* is a *low resistance* instrument. To measure

the amount of current flowing in a circuit, the ammeter must be connected *in series*. If it were of high resistance, it would reduce the amount of current because of its own resistance. The coil of an ammeter may be wound with a few turns of coarse low-resistance wire. It is more often wound in the same manner as the voltmeter, but it has a *low-resistance*

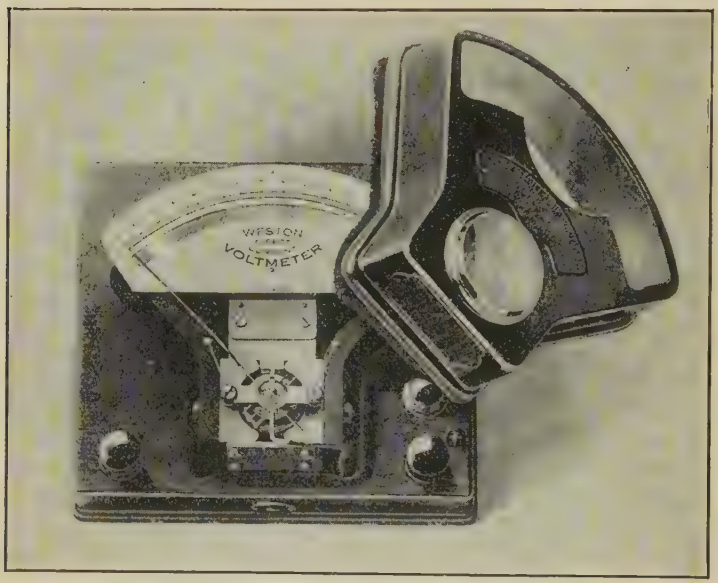


Fig. 635. — Voltmeter.

shunt connected across its terminals. Thus its resistance becomes almost negligible, since most of the current flows across the shunt. Fig. 636 shows the wiring diagram of an instrument that may be used either as a voltmeter or an ammeter. The plus terminal of the circuit is always connected to the binding post marked "volts or amps." When the other terminal is connected with the post marked "3 amps." as shown, the needle will read in amperes. Maximum is 3 amperes. It may also be connected to read a maximum of

1.5 amperes, or a maximum of 15 amperes. When connected successively to the terminals marked 3 volts, 15 volts, and 150 volts, the instrument may read from 0–3 volts, from 0–15 volts, or from 0–125 volts respectively.

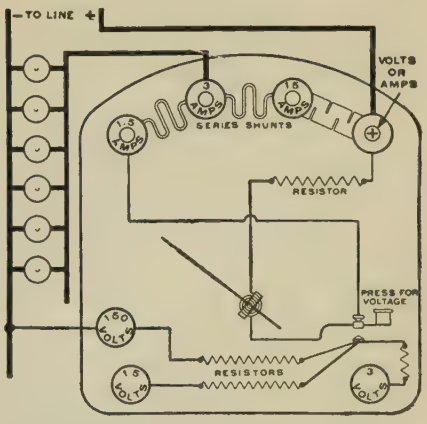


Fig. 636.—Voltmeter and ammeter diagram.

548. Rheostats or Resistance Coils. Rheostats, or resistance coils, are sometimes used to measure resistance; more often they are used to reduce the voltage in some part of a circuit, or to reduce the amperage. They consist of coils of high resistance wire which are so arranged that one or more coils may be thrown into the circuit in series. Fig. 637 shows how this may be accomplished. When the brass plug P is inserted, the current flows through the brass strips BB' instead of through the coil C, which has much greater resistance. When the plug from D is removed, the current then flows through the coil C'. Fig. 638 shows one type of resistance box. Each coil has a different resistance, and a wide variation in resistance may

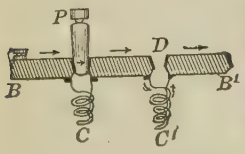


Fig. 637. — Resistance coils, showing winding.

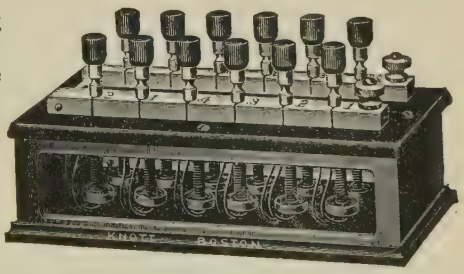


Fig. 638. — Rheostat, showing coils.

be produced by removing different plugs, or combinations of plugs. The wires used for resistance coils are often made of either manganin or constantan; these alloys have quite a high resistance, and their resistance is not much affected by temperature changes.

B. SERIES AND PARALLEL WIRING

549. Fall of Potential Along a Conductor. If we have two water tanks, C and D, connected with one another as shown in Fig. 639, the difference of pressure between the two tanks is represented by a water head of 45 feet. At the point A in the connecting pipe the pressure has fallen until it is represented by a water head of 30 ft. The difference of pressure between the point B and the surface of the water in the tank D is represented by a water head of 15 ft. There is a continuous fall of pressure along the connecting pipe. This fall of pressure is directly proportional to the length of the pipe.

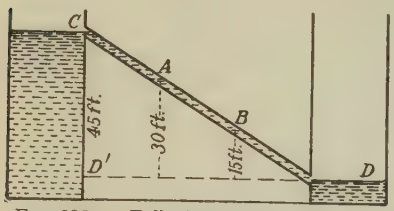


FIG. 639. — Fall of pressure is directly proportional to length of pipe.

A voltmeter connected to the terminals of a cell shows a *difference of pressure* of 2 volts. (See Fig. 640.) That is the *effective pressure* of the cell. Let us next connect the terminals of this cell with a wire 12 ft. long, and then test with a voltmeter the difference of potential between different points along the wire. When one terminal of the voltmeter is connected to the plate A, and the other terminal is connected to the wire at the point B, which is 6 ft. from A, we find that the difference of pressure

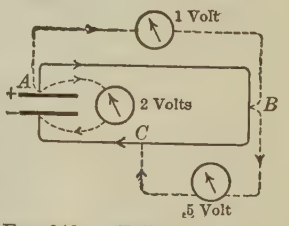


FIG. 640. — Fall of potential, resistance uniform.

is just one volt. If we connect the plus terminal of the voltmeter to B and the other terminal to the wire at C, just 3 ft. distant, the drop of potential is only 0.5 volt. Hence we conclude that the *fall of potential along a wire of uniform resistance is directly proportional to the length of the wire.*

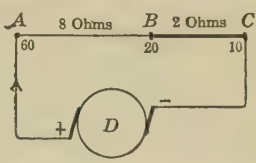


Fig. 641.—Fall of potential, resistance variable.

If the external resistance is not uniform, the fall of potential occurs, but it is not gradual. Suppose the dynamo of Fig. 641 maintains a constant P.D. of 50 volts between A and C; the resistance of AB is 8 ohms, and the resistance of BC is 2 ohms. The total resistance is 10 ohms; therefore a current of 5 amperes flows through the circuit. In order that 5 amperes may flow through AB, 8 ohms resistance, the P.D. between these points must be 40 volts. The P.D. between B and C must be 10 volts to send 5 amperes of current through 2 ohms resistance. From a consideration of these cases, it is evident that *the fall of potential is directly proportional to the resistance.*

Fig. 642.—No more water can flow through B than flows through A and C.

There is a drop of potential of 40 volts through the 8-ohm resistance and a drop of potential of 10 volts through the 2-ohm resistance. $40 : 8 = 10 : 2$. The student must remember that the current flowing in all parts of a series circuit is uniform. In the example just given, both the 8-ohm and the 2-ohm wires carry the same amount of current, 5 amperes. The water analogy helps to make this statement clear. (See Fig. 642.) It seems obvious that no more water can flow through the large pipes B and C than through the small pipe A. By analogy, we are led to conclude that no more current can flow through the small resistance of 2 ohms from B to C than that supplied to B from the 8-ohm wire AB.

550. Series Wiring. In a series circuit all the current flows through each appliance in turn. Suppose we have eight lamps L all connected in series with a 112-volt dynamo as shown in Fig. 643. If each lamp has the same resistance, 100 ohms, then the total resistance of the external circuit is 800 ohms, *the sum of all the separate resistances.* The amount of current flowing through the circuit is equal to $112 \div 800$, or 0.14 ampere. Each lamp receives the same amount of current. A voltmeter connected across the terminals of each lamp would show a fall of potential of 14 volts, since the fall of potential is proportional to the resistance.

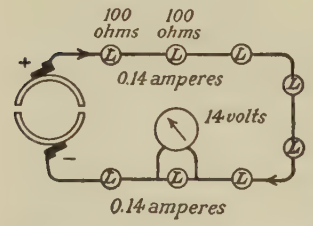


FIG. 643. — Potential drops from 112 to zero.

Series wiring has certain disadvantages. If one of the lamps shown in the diagram burns out, the others all go out, because the circuit is broken. Sometimes we would like to have more current flow through one appliance than through another, but this is impossible when they are wired in series. Each appliance *adds* its resistance to the resistance of every other appliance in the same series circuit.

In conclusion: 1. The *total resistance* in a *series*-circuit is equal to the *sum* of all the separate resistances. 2. The *current* in *all* parts of a *series*-circuit is the *same.* 3. The *fall of potential* in a *series*-circuit is *proportional to the resistance.*

551. Parallel Wiring. *Shunt or Divided Circuits.* If there are two equally good *parallel* automobile roads between Detroit and Chicago, normally each road will carry half the traffic. The congestion, or resistance, will be less than occurs when all the traffic moves over one road.

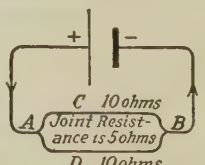


FIG. 644. — Parallel wiring, or shunt wiring.

In an analogous manner, we may connect wires in parallel or divided circuit. If the current from the positive plate, Fig. 644, divides at A, part of the current will pass through the branch C to B, and the rest will pass through the branch D. Let us suppose that each branch has a resistance of 10 ohms. *The total resistance of both branches is exactly half that of each branch.* Each branch carries half the current. The fact that the total resistance of a *shunt* or *divided* circuit is less than that of any branch usually astonishes the student. It will not be hard for him to understand, if he stops to consider that two parallel water pipes can carry with less resistance more water than a single pipe, or that traffic congestion is less over parallel streets than when all streets are closed to traffic but a single one. If we wish to empty a large building filled with people, there is less resistance when some use different doors than when the entire crowd uses a single exit only.

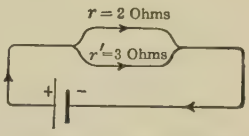


FIG. 645. — Shunt circuit.

In our study of divided circuits, we have found that the total resistance is $\frac{1}{n}$ of the resistance of a single conductor, provided each has the same resistance. Suppose, however, we have two wires connected in shunt with a voltaic cell, as shown in Fig. 645. The resistance r of one branch is 2 ohms, and that of the other branch r' is 3 ohms. We wish to find the joint resistance R of the two branches. If we define the *conductance* of a wire as the reciprocal of its resistance, then the total conductance equals $\frac{1}{R}$; the conductance of branch r equals $\frac{1}{r}$; and the conductance of branch r' equals $\frac{1}{r'}$. The total conductance equals the sum of the separate conductances.

Then $$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'}.$$

Substituting the known values, we have

$$\frac{1}{R}=\frac{1}{2}+\frac{1}{3}.$$

Whence, $R=1.2$ ohms.

PROBLEM. Three wires are joined in parallel. One has a resistance of 2 ohms; another a resistance of 3 ohms; and the third a resistance of 6 ohms. Find their joint resistance.

Solution. Substituting in the formula,

$$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'}+\frac{1}{r''},$$

we have $\frac{1}{R}=\frac{1}{2}+\frac{1}{3}+\frac{1}{6}$. Clearing of fractions, $12=6R+4R+2R$. Whence $12R=12$, and R equals 1 ohm, the joint resistance.

552. Current in Shunt Circuit. If there are two exits of equal width from a building, we would expect the same number of people to pass out each exit. Just so, if the two conductors of a divided circuit have the same resistance, we would expect half the current to flow through each branch. This is exactly what happens. If we have three parallel pipes from a water tank, all discharging into a water main, the total number of gallons per minute flowing in the main will equal the sum of the number of gallons per minute discharged by all the pipes. (See Fig. 646.) If we have more than two electrical conductors, all having the same resistance, then the amount of current flowing through each branch equals $\frac{1}{n}$ of the total current. In Fig. 647,

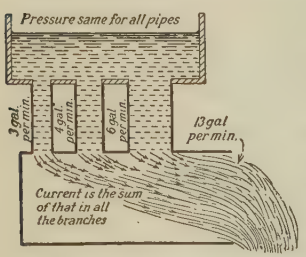

Pressure same for all pipes
3 gal. per min.
4 gal. per min.
6 gal. per min.
13 gal per min.
Current is the sum of that in all the branches

FIG. 646. — Current in main pipe equals sum of currents in all branches.

5 lamps each having a resistance of 220 ohms are wired in parallel. They operate on a 110-volt circuit. Their total resistance is $\frac{1}{n}$, or $\frac{1}{5}$, of 220 ohms, or 44 ohms. Hence the amount of current flowing in the *main circuit* is 2.5 amperes (110 ÷ 44). Each lamp carries $\frac{1}{5}$ of the current, or 0.5 ampere.

Just as more people can pass out through a *wide* door, so more current in a divided circuit flows through the branch of *less* resistance. If one of the two parallel roads between two cities is 40 ft. wide and the other is only 20 ft. wide, we would expect the broad road (less resistance) to carry $\frac{2}{3}$ of the traffic. Suppose in Fig. 645 the current in the main circuit is 5 amperes; then $\frac{3}{5}$ of the current will flow through the branch r of 2 ohms resistance, and only $\frac{2}{5}$ of the current will flow through the branch r' whose resistance is 3 ohms.

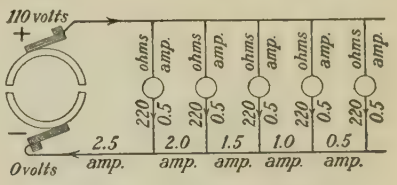


FIG. 647. — Parallel wiring.

PROBLEM. The two branches of a shunt circuit have resistances of 1 and 9 ohms respectively. If 30 amperes of current flow through the main circuit, what current will flow through each branch?

Solution. By analysis, the branch that has a resistance of 1 ohm will carry nine-tenths of the current, or 27 amperes; the 9-ohm branch will carry one-tenth of the current, or 3 amperes.

PROBLEM. Three appliances are connected in parallel on a 110-volt circuit. Their resistances are 22, 44, and 55 ohms respectively.

Find the amount of current flowing through each appliance. (See Fig. 648.) Find the current in the main circuit. What is the joint resistance?

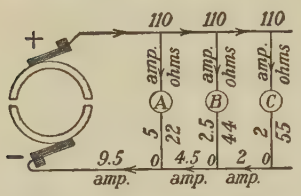


FIG. 648.—Current in the main circuit is equal to the sum of the current in the branches.

Solution. The difference of potential across the terminals of each appliance is 110 volts. Hence the current in appliance *A* equals $110 \div 22$, or 5 amperes. (Ohm's law.) The current through *B* equals $110 \div 44$, or 2.5 amperes. The current flow through appliance *C* equals $110 \div 55$, or 2 amperes. The current in the main circuit equals the sum of 5, 2.5, and 2, a total of 9.5 amperes. The joint resistance equals $110 \div 9.5$, or almost 11.6 ohms.

NOTE. Either method of solving such problems as the above may be used. Probably the latter method is the easier one.

In conclusion: 1. The *voltage* across the terminals of all the appliances in a parallel circuit is practically the same.

2. The *current flowing in each branch* of a two-branch circuit is inversely proportional to the resistance of that branch.

3. The *total current* in the circuit is equal to the *sum* of the currents in all the branches.

4. The *resistance* in each branch and the *total resistance* in the circuit may be found by Ohm's law.

553. Advantages of Parallel Wiring. If the lamps in our houses were wired in series, they would all go out when one was turned off. But since they are wired in parallel, it is possible to turn on any one or all, just as we wish. Our flat-iron takes about 5 amperes of current. By making the resistance of its coils 22 ohms, we can get that amount of current through the flat-iron by attaching it to a 110-volt circuit. In parallel with the flat-iron, we may connect a lamp which has a resistance of 110 ohms. Then 1 ampere of current will flow through the lamp. On a parallel circuit, we

may use any number of appliances, even if they require different amperages. Fig. 648 shows the current flowing through each of several appliances connected in parallel on a 110-volt circuit, and the current in the main circuit. Just as the tributaries to a river all add to the volume of water in the river, so all the branches of a parallel circuit add to the number of electrons flowing in the main circuit.

C. ELECTRIC POWER

554. Electric Power. The amount of chemical energy that is stored up when we charge a storage battery will depend upon the amount of current we use and upon the time that current flows. In fact the *capacity* of a storage cell is generally expressed in ampere-hours. For example, a cell of 20 ampere-hours capacity can supply a current of 1 ampere for 20 hours, or a current of 4 amperes for 5 hours. Thus we see that electrical energy may be delivered at a slow rate or it may be delivered rapidly. The rate at which electrical energy is delivered is called *electric power*.

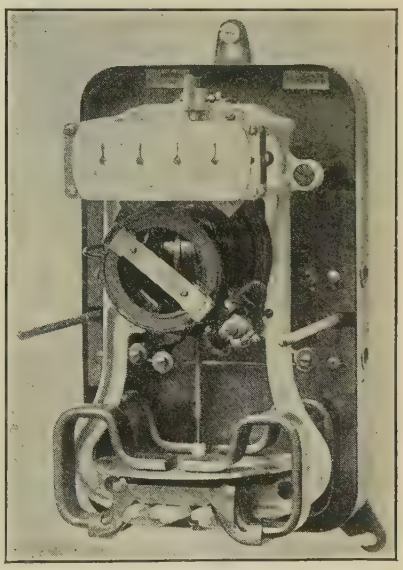


Fig. 649. — Watt-hour meter, D.C. (Direct current.)

The watt is the unit of electrical power. The watt equals a current of one ampere driven by a pressure of one volt. Hence, *volts* × *amperes* = *watts*. If the pressure is 1 volt, a current of 1 ampere flowing for one hour uses one *watt-hour* of

electrical energy. The consumer buys electrical energy at a certain price per *watt-hour*, or per *kilowatt-hour*. One kilowatt-hour equals 1000 watt-hours. If a flat-iron operating on a 110-volt circuit uses 5 amperes of current continuously for one hour, it consumes 550 watt-hours of electrical energy, or 0.55 kilowatt-hour.

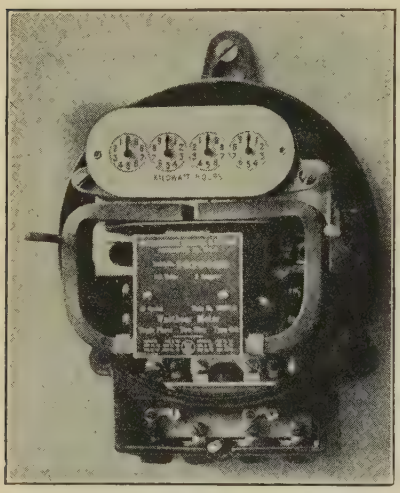


Fig. 650. — Watt-hour meter, A.C. (Alternating current.)

If we connect a voltmeter across the terminals of a circuit and an ammeter in series, we can find the rate of expenditure of energy in the circuit. The reading of the voltmeter in volts multiplied by that of the ammeter in amperes equals watts. Electric *watt-hour meters* are generally made to record their readings directly in kilowatt-hours. Different types of watt-hour meters are used for alternating and for direct current. (See Figs. 649 and 650.)

The right-hand dial of Fig. 651 reads by kilowatt-hours from 0 to 10; the next dial reads by 10's from 0 to 100; the third dial reads by 100's from 0 to 1000. The reading shown here is 1642 kilowatt-hours. An employee of the company supplying electricity reads the meter once a month. If this meter had read 1620 the preceding month, then the difference, or 22 kilowatt-hours, shows the amount of electrical energy consumed during the month.

Fig. 651. — Kilowatt-hour meter dials.

PROBLEM. A man uses four 40-watt lamps an average of 2 hours daily for one month. He uses two 100-watt lamps an average of 4 hours daily. A bread toaster which has a resistance of 20 ohms is used 20 minutes daily. A flat-iron in use a total of 20 hours per month takes 4.5 amperes of current. The voltage is 110. What is his electric bill for one month at a cost of 9 c. per kilowatt-hour?

Solution. $4 \times 40 \times 2 \times 30 = 9600$ watt-hours for the 40-watt lamps. $2 \times 100 \times 4 \times 30 = 24{,}000$ watt-hours for the 100-watt lamps. $110 \div 20 = 5.5$ amperes. $110 \times 5.5 \times \frac{1}{3} \times 30 = 6050$ watt-hours used by toaster. $110 \times 4.5 \times 20 = 9900$ watt-hours for flat-iron. Total consumption is the sum, which is 49,550 watt-hours, or 49.55 kilowatt-hours. The meter reading would be 49 kilowatt-hours. At 9 c. per kilowatt-hour, the bill would be $4.41.

D. MEASUREMENT OF RESISTANCE

555. How Resistance Is Measured. It is often necessary to measure the resistance of a conductor. Several methods are in common use:

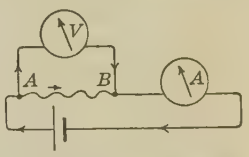


FIG. 652. — Voltmeter-ammeter method of finding resistance.

Voltmeter-ammeter method. This is one of the simplest methods of measuring resistances. A voltmeter which is connected *in parallel* across the terminals of the conductor AB, Fig. 652, gives the potential difference between the ends of the conductor. An ammeter *in series* with the conductor shows the amount of current flowing through the circuit. By Ohm's law, the resistance R equals $\frac{P.D.}{I}$.

Substitution method. Let us connect a few Daniell cells, grouped in series, with a sensitive galvanometer and the conductor whose resistance is to be found, as shown in Fig. 653. The amount of deflection of the needle is observed. Now if we substitute for the wire of unknown resistance a graduated resistance box, we can vary the amount of resistance introduced until the galvanometer reads the same as

before. The conductor must have the same resistance as that shown by the resistance box.

Wheatstone bridge method. If we put a water meter between two parallel water pipes, as shown in Fig. 654*A*, it will show that no current flows when both ends of the pipe have the same height. The pressure at both ends is the same. If the end *A* is raised to point *C*, for example, the water flows through *AB* to *B*. Conversely, raising the end *B* reverses the flow.

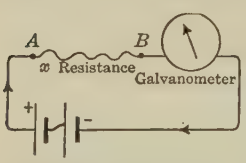


FIG. 653. — Finding resistance by substitution.

The Wheatstone bridge is analogous in principle. In Fig. 654*B* we place a galvanometer between the two wires of a parallel circuit. As long as the pressure at *A* is equal to that at *B*, no current will flow through the galvanometer *G*. Then the bridge is balanced. When we slide the end of the wire *C* along one branch of the circuit, we make the pressures unequal and current will flow through the galvanometer.

Next we shall introduce graduated resistance boxes at *R*, *R′*, and *R″* respectively, and the conductor of unknown resistance at *X*. (See Fig. 654*C*.) By varying the known resistances, it is possible to find a combination which produces no deflection in the galvanometer needle. When the bridge is *balanced* in this manner, then $R : X = R' : R''$. Since *R*, *R′*, and *R″* are known, *X* may be calculated.

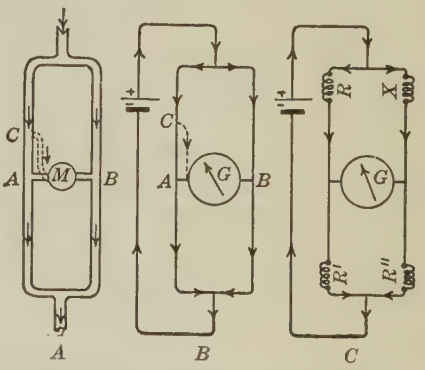


FIG. 654.— Wheatstone bridge. *A*. Water analogy. *B*. Bridge, unbalanced. *C*. Balanced bridge.

One form of Wheatstone bridge uses a uniform wire instead of the resistance coils R and R'. The galvanometer terminal is then slid along the wire until points A and B are of equal potential and no current flows through the galvanometer. In the equation given in the preceding paragraph, the length of one segment of wire is substituted for resistance R and the length of the other segment is substituted for resistance R'.

SUMMARY

A galvanometer is used to detect the presence of an electric current, to determine its direction, or to measure its pressure and strength. A high-resistance galvanometer calibrated to read volts directly is a voltmeter. A low-resistance galvanometer calibrated to read amperes is an ammeter.

The fall of potential along a conductor is directly proportional to its resistance. An ammeter shows the same reading in one part of a series circuit as in another part.

The joint resistance of several conductors in series equals the sum of the several resistances. When conductors are joined in shunt, the reciprocal of the total resistance equals the sum of the reciprocals of the individual resistances.

By the use of a voltmeter and an ammeter, the resistance of a conductor may be found directly. (Ohm's law.) Resistance may be found by substitution or by the use of a Wheatstone bridge.

The watt is the unit of electrical power. Volts times amperes equals watts. One kilowatt equals 1000 watts. Power companies usually charge for electrical energy at a certain price per kilowatt-hour.

QUESTIONS

1. Voltmeters are connected in parallel, and ammeters in series in electrical circuits. Give the reason in each case.

2. Which is more apt to be injured by the heating effects of an electric current, a voltmeter or an ammeter? Explain.

3. Why is a low-resistance conductor generally connected as a shunt across the terminals of an ammeter? Such an instrument is said to be "fool-proof." Explain.

4. Read your electric meter and record its reading. Read it again two weeks later and figure the cost of the electricity used during the two weeks' interval at the current price per kilowatt-hour.

5. New lamp bulbs usually have the power consumption in watts marked upon them. State clearly how you could use a few 40-watt lamps to check the accuracy of your meter.

6. Why must a voltmeter be a high-resistance instrument?

7. Why should an ammeter have a resistance which is practically zero?

8. What do you think would happen to an ammeter if you connected it across the terminals of an incandescent lamp? Explain. (Do not try the experiment.)

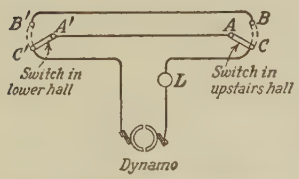


Fig. 655. — Three-way switch.

9. Why is it necessary to have the coils for resistance boxes made of special alloys?

10. Suppose an incandescent lamp is made to operate on a 110-volt circuit. How would the lamp be affected by operating it on a 120-volt circuit? How would it be affected if operated on a 100-volt circuit?

11. Most houses are now so wired that the light in the hall may be turned on or off from a switch in the lower hall or by means of a switch upstairs. Study the diagram shown in Fig. 655 and explain how either switch may operate the light *L*.

PROBLEMS

1. Five incandescent lamps are connected in series on a line whose total fall of potential is 550 volts. What is the difference of potential between the terminals of each lamp?

2. Five incandescent lamps are connected in parallel on a line whose total fall of potential is 110 volts. What is the fall of potential between the terminals of each lamp?

3. Three wires, having resistances of 4, 6, and 10 ohms respectively are joined in series. Calculate their joint resistance.

4. Calculate the joint resistance of the three wires of problem 3 when they are joined in parallel.

5. Resistance coils of 5, 7, and 13 ohms respectively are joined in series with a cell whose E.M.F. is 2 volts. If the internal resistance of the cell is 0.2 ohm, what current flows through the circuit?

6. Suppose the coils of problem 5 are all joined in parallel. What current will flow in the main circuit? Make a diagram.

7. Two wires, having resistances of 3 and 5 ohms respectively, are joined in parallel with a battery that has an E.M.F. of 18.75 volts. What current flows in the main circuit? What current will flow in each branch? Make a diagram before attempting to solve the problem.

8. A storage cell, E.M.F. equals 2 volts and internal resistance 0.1 ohm, is connected to the terminals of two coils in parallel. If the coils have resistances of 4 and 5 ohms respectively, what is their joint resistance? What current flows in the main circuit? What current flows in each branch?

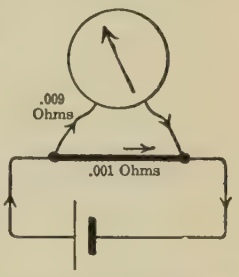


FIG. 656. — Shunt across ammeter.

9. Suppose an ammeter whose resistance is 0.009 ohm can carry safely 10 amperes. If it reads 10 amperes when connected in series, what will be its reading after a shunt of 0.001 ohm resistance has been connected across its terminals as in Fig. 656? How strong a current can then be used with the ammeter?

10. A voltmeter connected across the terminals of a dynamo shows an E.M.F. of 110 volts. Three lamps, A, B, and C, each having a resistance of 110 ohms are connected as shown in Fig. 657. When the lamp C is turned off, what current will flow through the ammeter? What current will flow when the lamp C is turned on? Explain why the lamp A will glow more brightly than either one of the others.

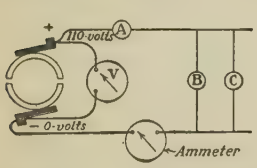


FIG. 657. — Series—parallel connection.

11. Lamps are rated in watts. How many watts does a 16 C.P. carbon filament lamp use if its resistance is 220 ohms and it is used on a 110-volt circuit? How many watts does it use per candle?

12. A tungsten lamp gives 32 candle power. When it operates on a 110-volt circuit, it uses 0.363 ampere of current. How many

watts does it use? How many watts per candle? Compare its efficiency with that of the carbon lamp of problem 11.

13. A flat-iron uses 4.5 amperes of current when operating on a 110-volt circuit. What is the cost of operating this flat-iron 4 hours at 10 cents per kilowatt-hour?

14. A coffee percolator has a heating coil whose resistance is 20 ohms. If it is used on a 120-volt circuit 30 minutes a day for 30 days, what will be the cost at 9 cents per kilowatt-hour?

15. The motor of an electric refrigerator uses 200 watts of electricity. The motor runs an average of 10 hours daily to keep the box cool. At a special power rate of 6 cents per kilowatt-hour, what is the monthly cost?

16. A man uses four 25-watt lamps an average of 2 hours daily; he uses eight 40-watt lamps an average of one hour daily; he uses a flat-iron like that of problem 13 a total of 16 hours per month. What is his total bill for a month of 30 days at the rate of 10 cents per kilowatt-hour?

17. A lamp uses 80 watts when operating on a 120-volt circuit. What is the current consumption in amperes? What is the resistance of the filament? What would be the resistance of three such lamps joined in series? Of three such lamps in parallel?

CHAPTER 26

INDUCED CURRENTS

A. HOW A CURRENT IS PRODUCED BY INDUCTION

Vocabulary

Dynamo, a machine which transforms mechanical into electrical energy.

Alternator, a machine which generates alternating current.

Stator, the stationary part of a generator or motor; it may be either the field or the armature.

Rotor, the rotating part of a generator or motor; it may be either the field or the armature.

556. Electro-magnetic Induction. As early as 1831, Michael Faraday studied the effect of a magnetic field upon a conductor moving through the field. We know from our study that a current in motion produces a magnetic effect. It seems reasonable to expect that a magnetic field might be used to produce electricity. Faraday showed that *a current is induced in a conductor when a magnet is so moved that its lines of force are intersected by the conductor.* The importance of this discovery by Faraday can hardly be overestimated. It led to the invention of the dynamo, which supplies current to run our street-cars, to light our houses, and for most commercial purposes where electricity is used.

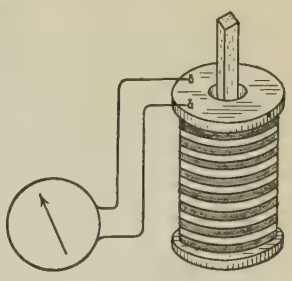


Fig. 658. — Magnet induces E.M.F.

Let us connect the terminals of a spool of wire to a galvanometer, as in Fig. 658, and then thrust one end of a bar

magnet down into the spool. The galvanometer needle is deflected, showing that a current is *induced* in the spool of wire. When the bar magnet is removed, an *induced current* is set up in the opposite direction. If we repeat the experiment, we find that more current is induced if we thrust the magnet into the spool or withdraw it *more quickly*. No current is induced when the magnet is *at rest* within the spool. If we use the other end of the magnet, the current directions are reversed.

557. Induction Occurs When the Conductor Moves Through a Magnetic Field. In the preceding section we moved a magnet so that its lines of force were cut by a conductor. Let us connect the terminals of a coil of wire to a galvanometer, and then thrust the coil down over one of the poles of a magnet, as shown in Fig. 659. A current is induced as in the former case. *If the circuit is closed, an induced current is always set up in a conductor when it cuts lines of force.* It does not matter whether the conductor moves across the lines of force of the magnet, or whether the magnet moves past the conductor. *One or the other must be in motion to produce an induced current.*

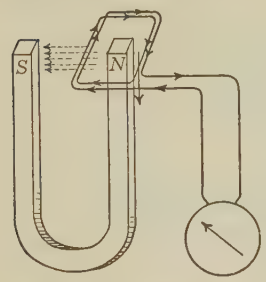
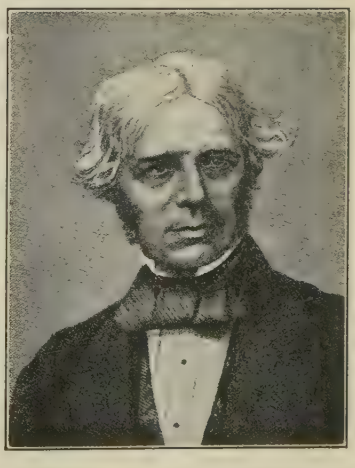


FIG. 659. — Electro-magnetic induction.

The student must distinguish between an *induced E.M.F.* and an *induced current.* If the ends of the coil of Fig. 659 are not connected, and the coil is on open circuit, then an *induced E.M.F.* is set up as the coil moves down over the pole of the magnet, but no current can flow. An induced E.M.F. has potential energy; if the circuit is closed, its energy becomes kinetic, and an *induced current* flows through the circuit. Other methods of producing an induced E.M.F. will be discussed in a later chapter.

558. Direction of Induced Current. When a wire is shoved down between the poles of a horseshoe magnet, as

Joseph Henry (1797–1878) was an American physicist. He developed the electro-magnet. He transmitted current through about a mile of fine copper wire and caused the armature of a magnet to be attracted. Henry is the inventor of the telegraphic principle and of the relay. He was the first to observe the phenomenon of self-induction. As Secretary of the Smithsonian Institution he founded the Weather Bureau.



Michael Faraday (1791–1867) was a distinguished English physicist and chemist. He was Assistant to Sir Humphry Davy at the Royal Institution. When the brilliant Davy was asked what he considered his greatest discovery, he is said to have replied, "Michael Faraday." Faraday liquefied certain gases. He discovered the laws of electrolysis. His researches in the field of induction led to the development of the dynamo and the magneto.

shown in Fig. 660, an induced E.M.F. is set up in the wire. If we close the circuit, an induced current flows. By connecting the ends of the wire to a sensitive galvanometer, it may be shown that the current flows in one direction as the wire moves *down* between the poles of the magnet, and in the reverse direction as it moves *up* through the magnetic field between the two poles. Cutting lines of force in one direction sets up a current in a conductor; when the conductor cuts lines of force in the opposite direction, the current is reversed. When the conductor moves parallel to the lines of force, no current is induced.

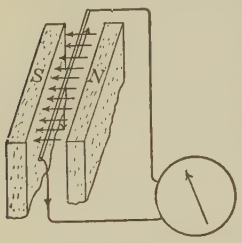


FIG. 660. — Conductor cuts lines of force.

The direction in which the induced current flows may be found by the use of the following right-hand rule, which is sometimes called the *dynamo rule: Let the extended fore-finger of the right hand point in the direction of the lines of force; turn the hand so the extended thumb points in the direction the conductor is moving; the middle finger, bent at right angles to both the thumb and fore-finger, will then point in the direction of the induced current.* Applying this rule to Fig. 660, we find that the current flows toward the observer as the wire moves up between the poles of the magnet; it flows from him as the wire moves down between the poles of the magnet.

Mr. Alton L. Hall of Bishop, California, uses the following rule: Hold the right hand with the fingers pointing in the direction of the lines of force. If the palm faces the direction of the moving wire, the thumb points in the direction of the current.

559. Lenz's Law. In § 557 we learned that an induced current is set up in a coil of wire as it moves down over the pole of a magnet. Of course in such a case the coil will

become a magnet. The induced current flows in such a direction that the magnetic pole of the moving coil *opposes* the field of the stationary magnet by repulsion. For example, if the coil is moving toward the N-pole of the magnet, the current will flow in such a direction that the face of the loop or helix approaching the N-pole will also become an N-pole. They repel each other, and try to prevent the coil from being lowered over the pole of the magnet. Hence work is done in overcoming this force of repulsion. When we try to remove the coil, the current reverses. Thus an S-pole is formed; this S-pole attempts to prevent the removal of the coil by its attraction for the N-pole of the magnet. Therefore work is done in removing the coil. These results may be summarized in a statement known as LENZ'S LAW: *An induced current set up in a moving conductor always flows in such a direction that it forms a magnetic field which opposes the motion of the conductor.* If the reverse were true, then we could create energy. If a dynamo could be built in which the reverse of Lenz's law could occur, then it would produce electricity without any steam or water power to drive it. But whenever an induced current is produced, it is done at the expense of some other form of energy.

If we thrust the coil down over the S-pole of the magnet, the current that is induced will flow in such a direction that the face of the coil approaching the magnet becomes an S-pole and opposes the motion. Lenz's law is merely another example of the fact that we cannot get something for nothing. Mechanical energy is *transformed* into electrical energy.

560. Strength of the Induced E.M.F. We have already seen that a higher E.M.F. is induced when a conductor moves rapidly through a magnetic field so that it cuts the lines of force faster. If we use a stronger magnet, there will be more lines of force to cut. Thus the stronger the magnet, the higher the induced E.M.F. When we double the number of loops in the coil, we double the number of conductors that are

cutting lines of force. Hence we increase the induced E.M.F. by increasing the number of loops. *The strength of the induced E.M.F. depends upon the number of lines of force cut per second.* Experiment shows that 100,000,000 lines of force must be cut per second to produce an induced E.M.F. of one volt.

In order to build up a high voltage by induction, *we may increase the strength of the field magnet, increase the speed of a rotating coil, or increase the number of loops in the coil.* In all of these ways, we increase the number of lines of force cut per second.

B. DYNAMOS AND ALTERNATORS

561. Induced Current in a Revolving Loop. To move a loop of wire up and down in a magnetic field is not a convenient method for producing an induced current. Instead, we may mount the loop on an axis so that it may be turned between the poles of the magnet by steam power or by water power. Fig. 661 shows a single loop of wire mounted on an axis so that it may be rotated by hand between the poles of a magnet; thus it cuts lines of force. Such an arrangement is a simple ideal dynamo. The *field magnet* furnishes the lines of force. The rotating loop, which we may call the *armature*, cuts the lines of force.

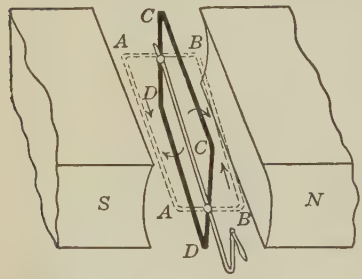


FIG. 661. — Simple ideal dynamo.

When the crank is turned, one wire of the loop moves down past the N-pole of the field magnet as the other wire moves up past the S-pole. By applying the dynamo rule, we find that the current encircles the loop in one direction during one half-revolution, and in the opposite direction

during the other half-revolution. The complete revolution is known as a *cycle*. A current that flows in one direction during part of a cycle and in the opposite direction during the rest of the cycle is called an *alternating current*. When a current flows in one direction only, it is called a *continuous* or *direct current*. The current in the armature of a dynamo is *alternating*.

With such a revolving loop, the E.M.F. rises to a maximum in one direction as one wire of the loop moves up past one pole, and then falls to zero when the wire is moving parallel with the lines of force. See Fig. 662, which represents the E.M.F. of a rotating loop during one complete cycle. As the wire moves down past the other pole, it is cutting lines of force in the opposite direction and the E.M.F. rises to a maximum in the other direction. The E.M.F. reaches a maximum when both wires of the loop are cutting a maximum number of lines of force, as at *AB*, Fig. 661. When the loop reaches the position shown at *CD*, no lines of force are being intersected, and the E.M.F. is zero.

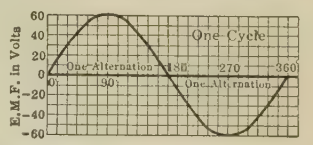


Fig. 662. — Alternating E.M.F. curve.

562. How Current is Taken from the Armature. If we were to connect the ends of a revolving loop direct to some instrument, the wires would be twisted off after a few revolutions of the loop. To utilize the current for work in an external circuit, the ends of the loop are soldered to two brass rings, called *slip-rings*, which are mounted on the same shaft as the loop. These rings are carefully insulated from each other so the current will not short-circuit through the loop. Two metal strips or carbon blocks, called *brushes*, rest lightly on the slip-rings as they

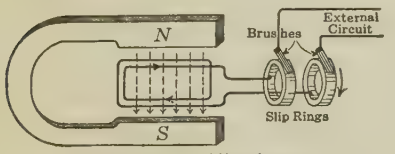


Fig. 663. — Slip-rings.

revolve with the loop. The ends of the wires used in the external circuit are connected to the brushes, which take current from the slip-rings and transmit it to the external circuit. (See Fig. 663.)

563. The Magneto. Since 100,000,000 lines of force must be cut per second to give an E.M.F. of one volt, the single loop of Fig. 661 furnishes too feeble a voltage to be of any practical value. In commercial machines the *armature* consists of a *large* number of loops or coils wound on an iron core. The simple H-armature devised by Siemens consists of a grooved iron cylinder wound with a large number of loops of insulated wire. (See Fig. 664.) By rotating such an armature rapidly between the poles of a strong magnet, a high E.M.F. can be obtained. In the *magneto*, several permanent horseshoe magnets are used as *field magnets*. The magneto generates an alternating current which is used extensively for ringing telephone bells, and with a spark-coil for ignition in gas engines.

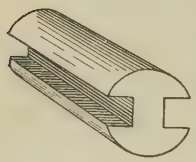


FIG. 664. — Siemens H-armature.

564. The Alternating-current Dynamo. *The dynamo is a machine for transforming mechanical energy into electrical energy.* It builds up a difference of potential between its terminals. Thus it can push or drive a stream of electrons through the appliances that are connected with it. The simple alternating-current dynamo differs from the magneto in only one important respect: the field magnet consists of a very strong *electro-magnet*. A. C. dynamos consist of three essential parts: (1) The *field magnet*, which produces lines of force; (2) the *armature*, which consists of an iron core wound with a large number of coils of insulated wire; the armature revolves on an axis between the poles of the field magnet, and in so doing cuts magnetic lines of force; (3) the *slip-rings* and *brushes*. All dynamos generate *alternating* current in the armature exactly as in the case of the single rotating

loop. When this current is taken from the armature by the brushes which rest on the slip-rings, the current in the external circuit is also *alternating;* that is, it flows through the external circuit first in one direction, and then in the opposite direction. Since there are two alternations for each revolution or cycle of the armature, and most commercial machines have a frequency of 60 cycles per second, the number of alternations is 120 per second. For use in heating, lighting, and certain power purposes the alternating current is satisfactory; hence *alternators* are extensively used. For electro-plating or for charging storage batteries, the alternating current cannot be used; it must be changed or transformed into a current that is *uni-directional*, or direct.

565. The Direct-current Dynamo. In only one particular does the *direct-current* dynamo differ from the alternator. The terminals of the armature are not connected to slip-rings, but to the segments of a commutator. The *commutator* (*commute*, to change) changes the alternating current of the armature into a current which flows in one direction *only* in the *external* circuit. Such a current is called a *direct* current, a *continuous* current, or even better, a *uni-directional* current, to distinguish it from the *alternating* current. In its simplest form the commutator consists of a ring of brass which has been split into two semicircular segments, carefully insulated from each other. The terminals of the armature coil are soldered one to each segment, as shown in Fig. 665. Brushes resting on these segments take current from them just as they do from the slip-rings of the alternator.

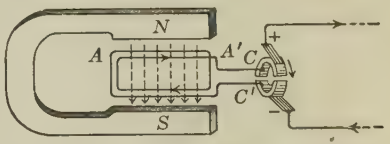


FIG. 665. — Commutator.

As the coil of Fig. 665 rotates so that the top wires AA' move toward the observer, the current flows to the commutator segment C. The brush bearing on this segment is receiv-

ing current; hence it is positive. As the armature rotates, the wires AA' of the loop begin to cut lines of force in an opposite direction, as in passing the S-pole they move from the observer. The current then reverses and flows to segment C'. But during this rotation of the coil or loop, the segment C' has also moved until it is now in contact with the positive brush. Therefore the brush marked plus always rests on the segment *to* which the current from the armature is flowing. Thus the current is *alternating* in the armature, but *continuous* in the external circuit. The brushes are so adjusted that the commutator segments change from one brush to the other at the same instant the current reverses in the armature. While segment C is receiving current, it is in contact with the positive brush. While segment C' is receiving current, it is in contact with the positive brush.

FIG. 666. — Direct E.M.F. curve. Single loop.

When only one coil or loop is used in the armature, the E.M.F. is pulsating, or intermittent, as shown in the curve of Fig. 666. To secure a more constant voltage, a large number of coils is used in the commercial dynamo. They are set at angles to one another, so that some coil is always cutting lines of force.

C. ARMATURES AND MAGNETIC FIELDS

566. The Drum-wound Armature. The core of a drum-wound armature is built up of iron discs like that shown in Fig. 667. These discs are so mounted on an axis that grooves are formed in which the insulated wires are wound, first along one groove, then across the end of the drum, and back along the groove on the opposite side. The ends are attached to commutator

FIG. 667. — Slotted disc, for armature.

segments. A large number of coils is used, each coil requiring two commutator segments.

The discs are insulated from one another to prevent *eddy currents* being set up in the iron core by induction. Eddy currents heat the core and cause a waste of energy. The holes

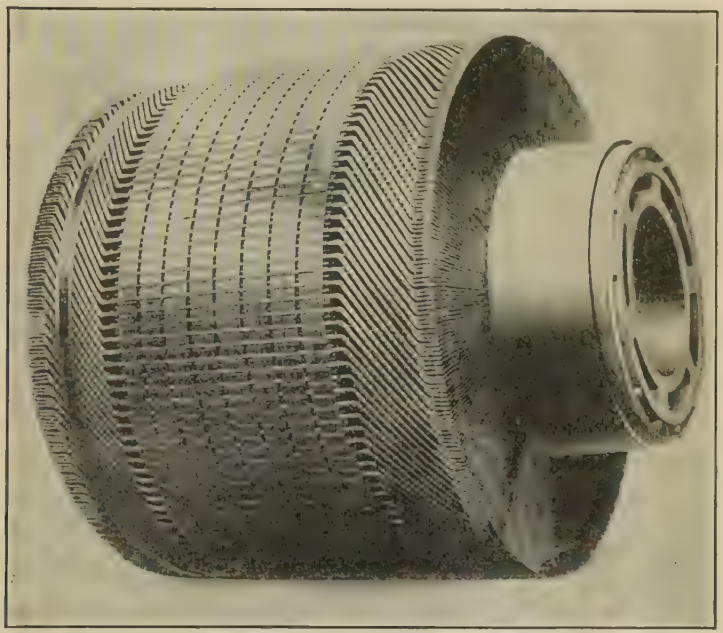


FIG. 668. — Drum armature. The ends of each loop are connected to the commutator segments.

in the discs permit the air to circulate through the core to carry away waste heat. Fig. 668 shows a *drum-wound armature* of the commercial type.

567. Ring-wound Armature. In the *ring-wound armature* the insulated wire is wound in the form of a spiral on an iron ring or shell, as shown in Fig. 669. The wires on the inside of the ring and also those at the ends *do not cut* lines of force.

The lines of force follow along the iron ring from one pole to the other, since the iron is more permeable than the air-gap in the center of the ring. Note the dotted lines of the figure. With the drum-wound armature all the wires except the segments at the ends cut lines of force.

The ring-wound armature wastes wire if used for armatures of small diameter. When an armature of large diameter is drum wound, much wire is wasted at the ends; in such

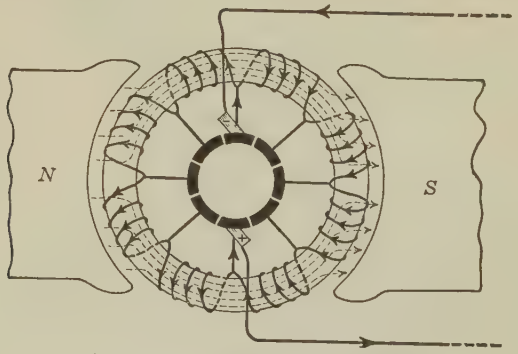


FIG. 669. — Ring-wound armature.

cases ring-winding is less wasteful. It is easier to insulate the winding of the ring type and more convenient to make repairs. The ring-wound armature is used for high voltage work.

568. How the Field Magnet is Magnetized. In the *magneto*, permanent magnets are used to furnish the lines of force. With the dynamo and alternator, current must be supplied from some source to energize the field magnets. Sometimes the field is magnetized by current from an outside source, a number of storage cells for examples. (See Fig. 670.) For *alternators* a small direct-current dynamo, called an *exciter*, is generally used for this purpose. By this means the current through the field is kept constant, and the voltage of the alternator does not vary if its speed is uniform.

Most *direct current dynamos* are *self-exciting* machines. They furnish current to energize their own magnetic field.

569. Self-exciting Machines. With a direct current dynamo, a part or all of the current induced in the armature may be conducted through the wires of the field magnet to energize it. Such self-exciting machines are of three different types: 1. *Series-wound;* 2. *shunt-wound;* 3. *compound-wound.* To start a new dynamo, the field must be magnetized by some outside source. When the dynamo stops, the field loses nearly all its magnetism, but enough *residual* magnetism is left in the pole-faces to build up enough voltage to cause an induced current in the armature. This current, or part of it, flows through the wires of the field and energizes the field.

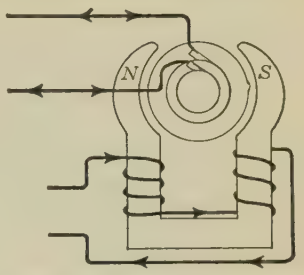


FIG. 670. — The field of an alternator is magnetized by storage cells or by a small D.C. dynamo.

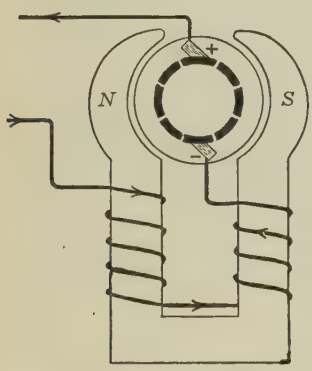


FIG. 671.—Series-wound dynamo.

If we study Fig. 671, we see that the wire from one of the brushes is coiled around the cores of the field magnet. Thence it goes to the external circuit. This is a *series-wound dynamo.* If the external resistance of such a dynamo is increased, less current flows through the circuit. This means that less current flows through the field and its strength is decreased. Fewer lines of force are then cut per second, and the voltage falls. If the load is always the same, such a dynamo is satisfactory. It is used with arc lamps, when all the lamps are lighted at the same time. It may be used

for other work, provided a storage battery can be used to help energize the field.

In the dynamo shown in Fig. 672, we find that two wires lead from the positive brush. One goes out to the *external* circuit. The other is a shunt wire which is wound around the cores of the field magnet and then connected to the negative brush. Thus only a part of the current is used to energize the field. This is a *shunt-wound* dynamo. The shunt circuit has many turns of smaller wire. If we increase the resistance of the external circuit, then more current will flow through the field, and the voltage of the machine rises.

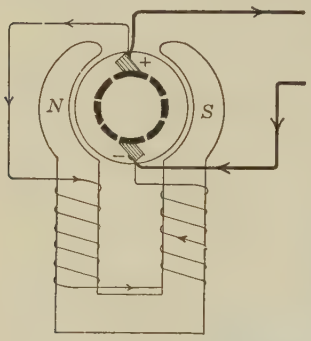


Fig. 672.—Shunt-wound dynamo.

The merits of the series- and shunt-wound dynamos are combined in the *compound-wound dynamo*. Fig. 673 shows that it is a combination of the two methods of winding just discussed. An increase in the resistance of the external circuit reduces the current in the *series coils*, but it increases the current in the *shunt coils*. It is possible to so adjust the number of coils in each winding that a compound dynamo will give quite a constant voltage, even under varying load.

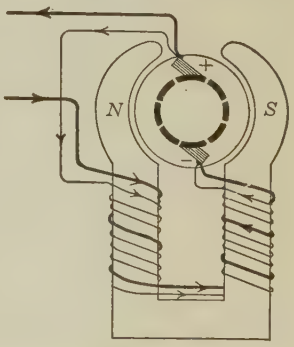


Fig. 673. — Compound-wound dynamo.

570. Alternating and Direct Current Compared. The *direct current* may be used for heating, lighting, electro-plating, charging storage batteries, electro-magnets, running

motors, and practically any kind of electrical work. The *alternating current* cannot be used for electro-plating or any kind of electro-chemical work. It cannot be used to charge storage batteries without the aid of some charging device.

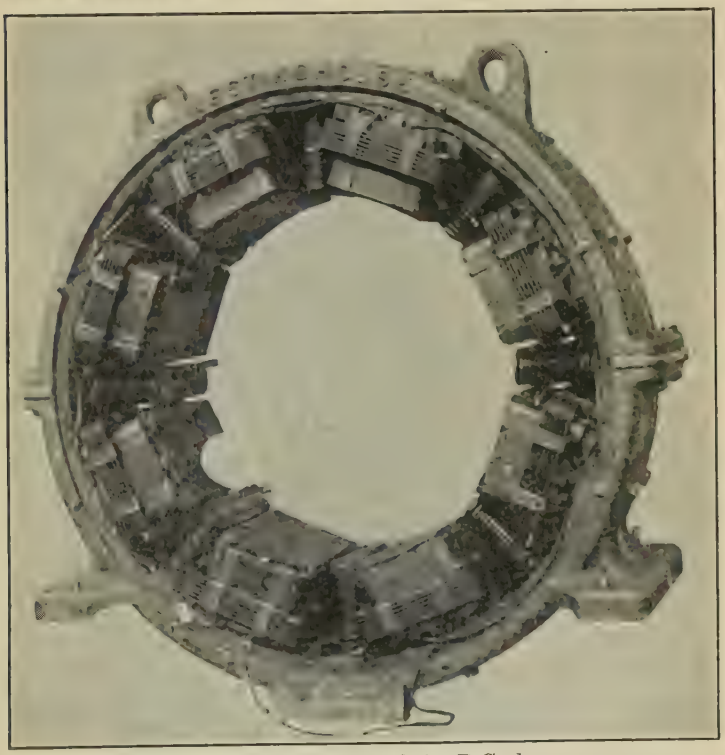


Fig. 674. — Eight-pole field, for D.C. dynamo.

It may be used for running motors, for heating, and for lighting, although it is not so satisfactory as direct current for arc lighting. When it is used to make an electro-magnet, the poles of the magnet are reversed with each alternation. The alternating current has one great advantage over the direct current. The voltage of an alternating current may

be raised or lowered just as desired, and there is very little loss of energy during such changes. There is no practical method of raising the voltage of a direct current after it leaves the dynamo. It may be lowered by the use of resist-

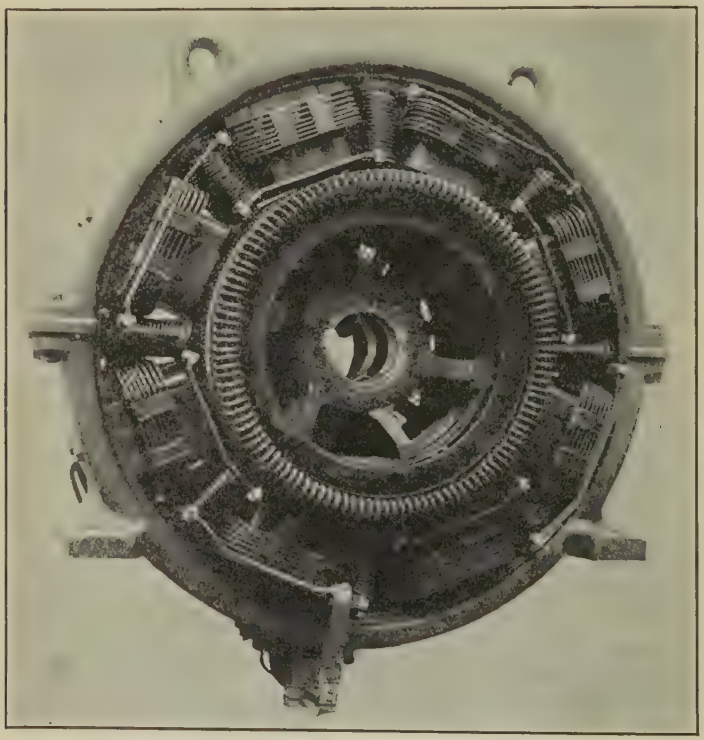


Fig. 675. — Eight-pole direct-current dynamo.

ance, but there is a tremendous loss of energy. For distance transmission, alternating current is always used.

571. Alternators and Dynamos Compared. In commercial dynamos multipolar machines are used. Fig. 674 shows an *eight-pole* field for a direct-current dynamo. The drum-wound armature of Fig. 674 is shown in position in the field

in Fig. 675. While a two-pole field has one cycle and two alternations per revolution, a four-pole machine has two cycles and four alternations per revolution. An eight-pole machine has four cycles and eight alternations per revolu-

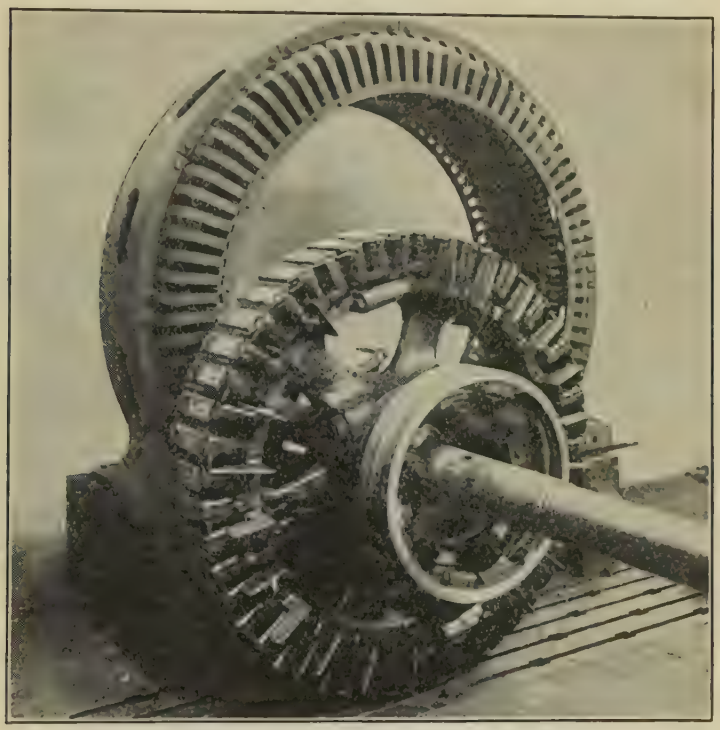


Fig. 676. — Rotor and stator of a commercial alternator.

tion. If direct current is needed, the alternating current from the armature must be changed to direct current by means of a commutator. A direct current is not suitable for very high voltages, since it becomes increasingly difficult to insulate the commutator segments as the voltage rises.

For incandescent lighting, an alternator having a frequency

of 60 cycles per second is generally used. For power transmission, a frequency as low as 25 cycles per second is commonly used. With 60 cycles there are 120 alternations per second. If we bear in mind the fact that the duration of vision is never less than $\frac{1}{20}$ of a second and that these alternations occur at intervals of $\frac{1}{120}$ of a second, we can understand why there is no flickering in an incandescent lamp. In very high voltage alternators the armature is stationary,

FIG. 677.— Note the great length of this rotor for a 100,000 KV–A generator which will supply current for a city of 500,000 people.

and the field magnet rotates inside the armature. The stationary armature, which is called a *stator*, is shown in Fig. 676. The rotating field is called the *rotor*. Since the current is taken from the stationary armature without the use of slip-rings and brushes, the difficulties involved in insulation are decreased decidedly. Figs. 677 and 678 show the stator and rotor of the largest single-unit generator ever constructed. It produces about 133,000 horse power. One gets some idea of the enormous size of such a generator by comparing the diameter of the stator with the height of the man inside.

D. THE ELECTRIC MOTOR

572. The Electric Motor. Let us mount an electro-magnet on an axis so that it is free to rotate as an armature between the poles of a magnet, as shown in Fig. 679. Now if we pass current through the electro-magnet in such a direction that the pole at the top of the figure is an S-pole, it will be attracted by the N-pole of the stationary magnet and repelled by the S-pole. Inertia would carry it a little beyond the N-pole. If at that particular instant the direction of the current flow in the rotating magnet is changed, then the poles will be reversed. (See Fig. 680.) The stationary poles of the field continue to drive the rotating magnet around through 180° by their attraction and repulsion. Another reversal of the current and change in the polarity of the armature, and the forces of repulsion and attraction drive and pull the armature through another half-circle. By means of a commutator, the current can be reversed at just the right instant to keep the armature magnet revolving continuously. Thus we have the principle of the electric motor.

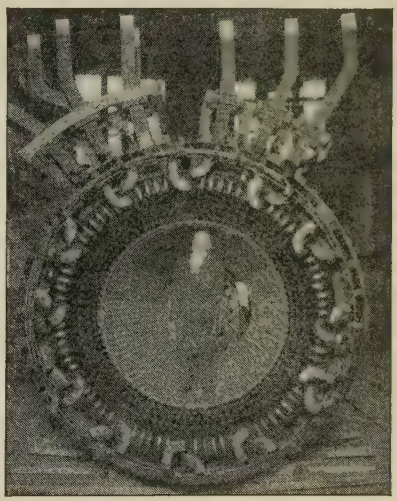


FIG. 678.— Stator for the rotor of Fig. 677. Note the diameter.

The electric motor transforms electrical energy into mechanical energy. It does not differ in construction from the direct-current dynamo. Current from a dynamo or some other source is led into an electric motor; there it produces two

magnetic fields, one in the field magnets and the other in the armature. These two magnets attract and repel one another with sufficient force to cause the armature to rotate rapidly. The power from the motor is transmitted to the *driven* machine by a belt wheel attached to the axis of the armature or directly by means of gear-wheels.

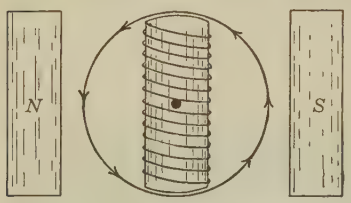


FIG. 679.— Armature rotates between poles of field magnet.

By the use of Fig. 681, we may explain in detail why the armature of a motor rotates. As the current flows through the armature loop in a counter-clockwise direction, the loop becomes a magnet with its N-pole toward the observer, and its S-pole from him. The north pole of the field magnet repels the N-pole of the loop and attracts its S-pole. The south pole of the field magnet at the same time attracts the N-pole of the loop and repels the S-pole. These forces of attraction and repulsion all work together to turn the armature in the direction shown by the dotted arrow. If the current continued to flow in the same direction, the

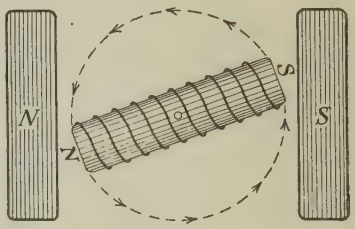


FIG. 680. — Current change reverses polarity.

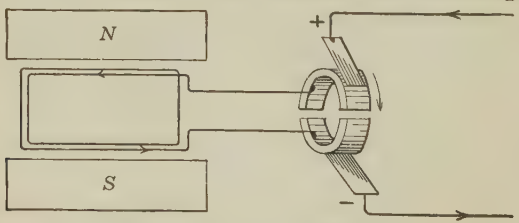


FIG. 681. — Motor diagram.

rotation of the armature would stop as soon as the N-pole reached a position adjacent to the south pole of the field. But when this point is reached, the commutator reverses the direction of the current which enters the armature, its polarity is reversed, and mutual attraction and repulsion

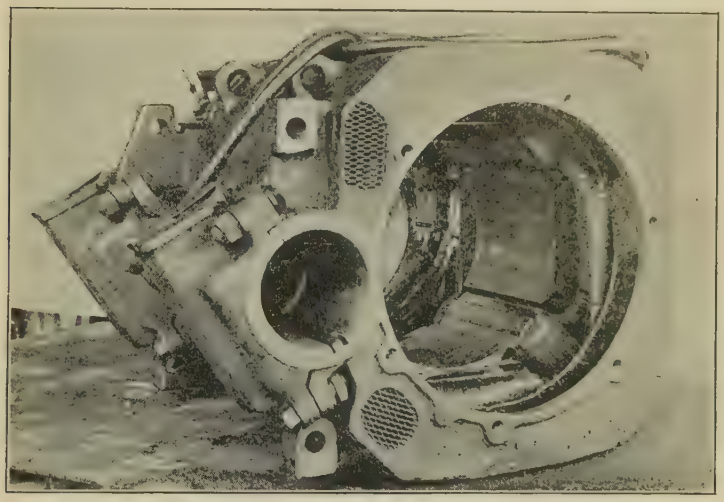


Fig. 682. — Magnetic field of street car motor.

occur as before. Inertia carries the poles past the points of dead center.

The direction of rotation may be found by the use of the *left-hand rule*, or *motor rule*. Extend the fore-finger of the *left* hand in the direction of the lines of force; turn the middle finger, bent at right angles to both the thumb and fore-finger, so that it points in the direction of current flow. The extended thumb then points in the direction of rotation.

The *torque*, or tendency to produce rotation, of a motor armature depends upon the strength of the current and upon the winding of the field and armature; since the strength of an electro-magnet depends upon the number of ampere-turns,

the torque or twisting force of the armature depends upon the mutual attraction and repulsion of the field magnet and the armature.

573. Series and Shunt Motors. Direct-current motors may be shunt-wound or series-wound. *Shunt motors* are extensively used in machine shops since their speed is not

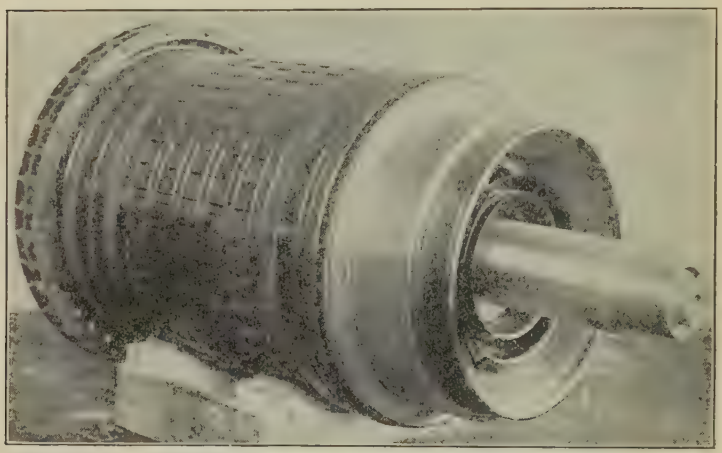


FIG. 683. — Armature for D.C. street car motor.

much affected by varying loads. Fig. 682 shows the magnetic field of a street-car motor. The armature is shown in Fig. 683. *Series motors* are used on automobiles and street-cars. The torque of a series motor is much greater at starting than

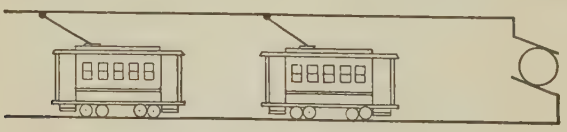


FIG. 684. — Street cars are operated in parallel.

that of a shunt motor. Hence the series motor is used when a motor must start under load. In street-car motors, the armature is connected with the load by means of gear-wheels,

which at the same time reduce the speed. A series motor is the only type that will run on either direct or alternating current. Hence it is used extensively in small motors for turning fans, vacuum cleaners, sewing machines, etc. The current reverses in the field at the same time as in the armature; hence such a motor will run on alternating current. Street cars are generally operated at a voltage of 550. The

FIG. 685. — The largest electric locomotive in the world. The total length is 152 ft., and the weight is 637.5 tons. This locomotive, which has a maximum horse power of 7,125, can pull with a force of 115 tons. In hauling heavy trains over the Allegheny Mountains, the armatures of the motors generate current on the down grade. Thus they act as brakes and also supply current to the line.

current is supplied to the motor from a trolley wire or a third rail. The current flows through the car-wheels to the track, which forms the return circuit, Fig. 684. The Virginian electric locomotive is shown in Fig. 685.

574. Alternating-current Motors. Of the several types of alternating-current motors that are in use, only one type will be discussed. The *induction* motor consists of two parts; the *stator*, which differs little from the stator of an alternator in the manner in which it is wound; and the *rotor*, which is built of copper bars laid in slotted, laminated iron cores. In

the type known as the *squirrel-cage rotor* the copper bars are all connected at each end to copper rings, Fig. 686. When an alternating current passes through the windings of the stator, a rotating magnetic field is set up. The rotor is not

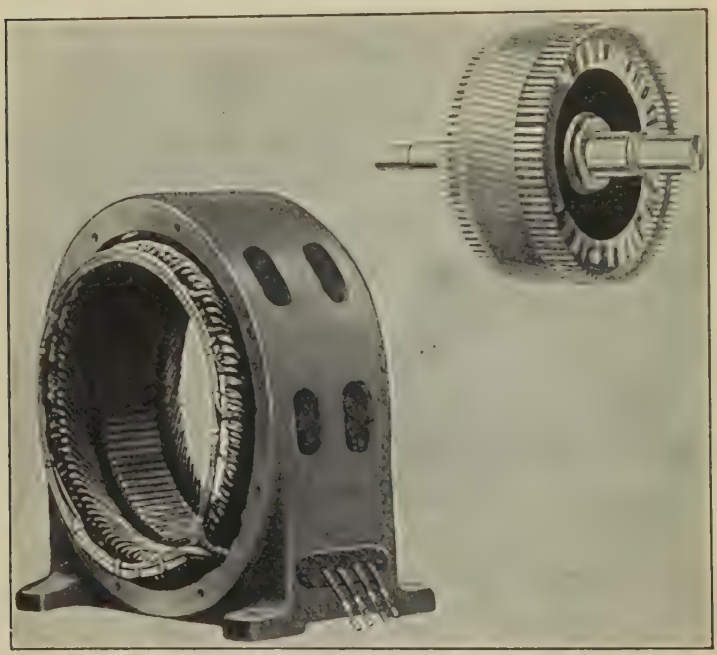


Fig. 686. — Squirrel-cage induction motor. The lower view shows the stator base; the upper view shows the rotor.

connected in any way to the stator or the electrical supply, but the rotating magnetic field produces a current in the rotor by induction. The magnetic field set up in the rotor by this induced current is dragged after the rotating magnetic field in the stator. Thus the rotor turns very rapidly on its axis. Induction motors are made in all sizes; their advantage lies in their simplicity.

575. Back E.M.F. Developed by a Motor. Suppose we connect an incandescent lamp in series with a small motor on the lighting circuit. If the armature is held so that it cannot rotate, the lamp glows brightly. When the armature is released, the light will grow dimmer as the motor comes up to full speed.

The voltage from the lighting circuit is *impressed* upon the motor. When the armature of the motor rotates in the magnetic field of the motor, it is cutting lines of force and producing an E.M.F. In accord with Lenz's law, this E.M.F. produced by the motor is a *back E.M.F.*, or a *counter E.M.F.* The back E.M.F. opposes the impressed E.M.F. The *effective* voltage which drives the motor is equal to the *difference* between the impressed E.M.F. and the back E.M.F. Thus we see that *every motor when running is also a generator.*

If a motor whose resistance is only 5 ohms is attached to a 110-volt circuit, 22 amperes of current will flow through the armature when it is at rest. If the same armature, when running at full speed, cuts lines of force fast enough to produce a counter E.M.F. of 100 volts, then the effective voltage is equal to $110 - 100$, or 10 volts. The resistance does not change, but now only 2 amperes of current will flow through the armature of the motor.

Thus we find that the back E.M.F. of a motor which is running without load must be almost equal to the impressed E.M.F. Just enough current flows through the motor to overcome friction. If the armature slows down under load, then the back E.M.F. falls and more current flows through the armature. Thus a motor adjusts itself to a varying load. Motors are *more economical* than other electrical appliances, heating appliances for example, because the counter E.M.F. reduces the amount of current and the power consumption.

576. Starting Motors. The resistance of a motor armature is very low. For that reason the armature of a large

motor is likely to be "burnt out" if the full current is turned on before the motor is brought up to speed. After it has been brought up to speed, then the full current may be used,

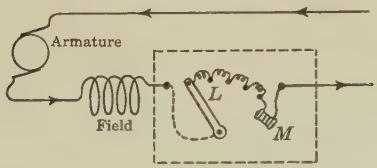


FIG. 687. — Starting box, series motor.

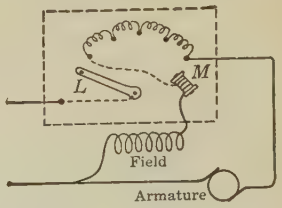


FIG. 688. — Starting box, shunt motor.

because the back E.M.F. opposes the impressed voltage and reduces the amount of current as discussed in § 575. Small motors have little inertia and come up to speed so quickly that the overload at starting may be safely carried for the few moments needed to develop a counter E.M.F. In starting large motors, rheostats are used to protect the motor. The resistance is then cut out gradually as the speed of the armature increases. Fig. 687 shows how a starting box is used with a series motor. Several coils of resistance wire are connected in series with the motor. As the speed increases, one coil after another is cut out by shoving the lever L to the right.

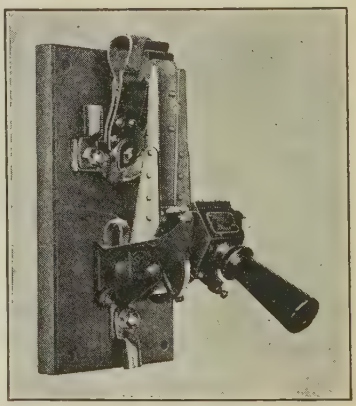


FIG. 689.—Automatic circuit breaker.

In starting a *shunt-wound* motor the resistance in the field is increased as the resistance in series with the armature is gradually cut out. (See Fig. 688.) Both of these operations increase the current flowing through the armature, and thus increase the speed of the motor.

577. Circuit Breakers. Sometimes an overload might decrease the speed of a motor suddenly. Then there would be a rush of current through the armature that might ruin it. An automatic circuit breaker opens the circuit in such an event and prevents injury to the motor. (See Fig. 689.) Frequently the motorman on a trolley car cuts out resistance too rapidly when a car is gaining speed. Then the circuit

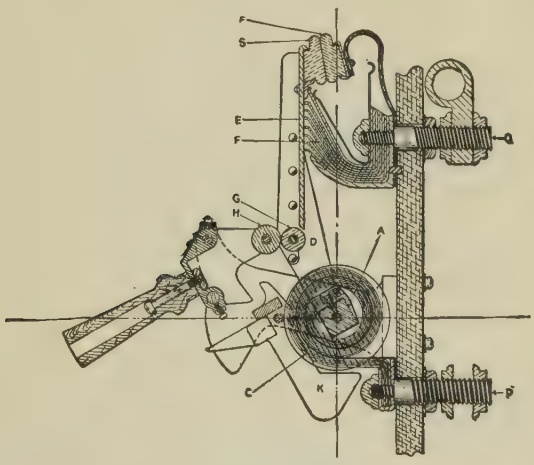


Fig. 690. — Circuit breaker diagram.

breaker automatically opens the circuit with the sharp report which is familiar to all. The motorman then throws in more resistance and closes the circuit again by means of a small lever.

Circuit breakers are of two types; *overload* and *underload.* In the overload circuit breaker of Fig. 690, the current enters through stud P and flows through the strap windings C into the arm D; thence it flows through the contact plate E into the stationary brush F, which is connected with the stud Q. The square core A is magnetized to a degree which depends upon the current strength. When an overload

occurs, the core becomes so strongly magnetized that the end K of the pivoted armature is lifted enough to release the handle. The resiliency of the coil C then throws the arm outward and breaks the circuit, first through the brush fingers F and the contact plate, and finally between the carbon blocks F and S. The breaker is reset by pulling the handle down, thus bringing the roller H into engagement with roller G and forcing the arm back into its initial position.

The underload circuit breaker is especially useful when storage batteries are being charged. If the voltage of the dynamo that is being used to charge the batteries should be momentarily lowered below that of the batteries themselves, a current would flow back through the dynamo and cause it to run as a motor. An underload circuit breaker may be set to break the circuit automatically if the voltage falls below a predetermined value.

SUMMARY

An induced E.M.F. is produced in a conductor when it cuts lines of force. The induced current set up in a closed conductor cutting lines of force opposes the motion of the conductor through a magnetic field. Its strength depends upon the number of lines of force cut per second. An induced E.M.F. of one volt is produced when 100,000,000 lines of force are cut per second.

The dynamo transforms mechanical energy into electrical energy. The current in the armature alternates twice during each revolution. By means of a commutator, the alternating current may be converted into a uni-directional current in the external circuit.

The armature of a dynamo may be ring-wound or drum-wound. The field magnets may be excited by means of an independent current, or the machine may be self-exciting. A self-exciting machine is series-wound, shunt-wound, or compound-wound.

The electric motor transforms electrical energy into mechanical energy. Since it cuts lines of force it also produces an induced E.M.F., which opposes the E.M.F. from the line wire.

QUESTIONS

1. Why is it impossible to charge a storage battery by using an alternating current?

2. A ship having an iron mast sails east. A wire running along the mast is connected at the top and bottom so that it makes a loop with the mast. Is an induced current set up in the wire? Is an induced E.M.F. produced? Does it matter whether the plane of the loop is coincident with or perpendicular to the earth's magnetic field?

3. Do you think there would be an induced current set up by a loop of wire revolving on a vertical axis in the earth's magnetic field? Explain.

4. What advantage has the magneto over the dynamo? What advantage has the dynamo over the magneto?

5. Some years ago the following query was sent to a scientific magazine: "I have a $\frac{1}{2}$ H.P. hand dynamo. It turns easily until I connect the dynamo with my motor; then it turns hard. What is the matter with my dynamo?" How would you answer this query?

6. Explain in detail why the armature of an electric motor rotates continuously.

7. Compare the cost of running a vacuum cleaner or an electric fan with that of operating an electric flat-iron or toaster.

8. Make a list of as many household appliances as you can that make use of the electric motor.

9. Why is a series-wound motor used with the self-starter of an automobile?

10. Why are both starting boxes and automatic circuit breakers needed for use with large motors?

11. Since the amount of current flowing through street car rails is almost the same as that flowing through the trolley wire, why do we receive a more severe shock by touching the trolley wire?

PROBLEMS

1. An electric fan operating on a 110-volt circuit uses 1 ampere of current. What will be the cost of operating this fan for 10 hours at 9 cents per kilowatt-hour?

2. An electric refrigerator has a motor that uses 150 watts of electrical power. What is the horse power of its motor? If this motor runs an average of 10 hours per day for 30 days, what will be the cost of operating it at a power rate of 5 cents per kilowatt-hour?

3. A motor operating on a 110-volt circuit develops a back E.M.F. of 90 volts. The resistance of the armature is 4 ohms. What current will flow through the motor? What will be the cost of operating this motor for 10 hours at 10 cents per kilowatt-hour?

CHAPTER 27

ELECTRO-MAGNETIC INDUCTION

A. INDUCTION BY VARYING A MAGNETIC FIELD

Vocabulary

Transformer, usually refers to a device for changing the voltage of an alternating current.

Rectifier, a device used to change alternating current to direct current, or the reverse.

Reactance, a choking effect due to self-induction; inductive resistance.

Impedance, the joint effect of reactance and resistance in alternating current circuits.

578. How a Battery Current May Produce an Induced Current. Let us connect to the terminals of a galvanometer a coil consisting of a large number of turns of fine insulated wire. We may call this coil the *secondary coil.* Then let us place inside the secondary coil a small coil wound with a few turns of coarse wire. This coil, which is called the *primary coil,* is joined in series with a dry cell and a contact key, as shown in Fig. 691.

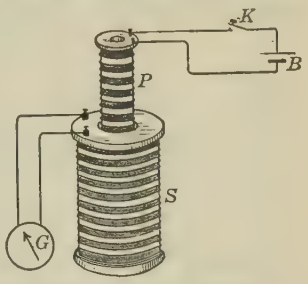


FIG. 691. — Varying field induces E.M.F.

When the contact key is pressed, a current flows through the primary coil. The galvanometer needle is deflected, showing that a *current is induced in the secondary coil.* The lines of force produced by the current flowing in the primary coil *cut across* the wires of the secondary coil and produce an induced current in the secondary. When the key is held firmly, the induced current soon ceases to flow. If the

circuit is broken, a current is induced in the *opposite* direction. As the strength of the magnetic field produced by the current in the primary rises to a maximum, the lines of force cut across the secondary and induce current. When the strength of the magnetic field falls from its maximum to zero, an induced current of opposite direction is set up. *Hence we conclude that increasing or decreasing the number of lines of force in a magnetic field induces an E.M.F. in a conductor present in that field.* If the circuit is closed in the secondary, an *induced current* is produced. No current is induced, however, unless the strength of the magnetic field is *varied.*

579. The Induction Coil. It is possible to produce an intermittent current by opening and closing the contact key of Fig. 691. But it is more convenient to substitute for the contact key a vibrator which will "make" and "break" the circuit automatically. Then we have the essentials of a *spark coil* or an *induction coil.* The coil shown in Fig. 692 uses a vibrator essentially like the armature of an electric bell. The current flows from the positive plate of the voltaic cell *B* through the heavy wire of the primary coil and returns to the negative plate through the vibrator *V* and the post *P*. The primary coil consists of a few turns of coarse wire wound on a bundle of iron wires, insulated from each other to prevent *eddy currents.* The secondary coil consists of many thousands of turns of insulated wire wound on a spool which surrounds the primary. Sometimes miles of fine wire are used on the secondary coil.

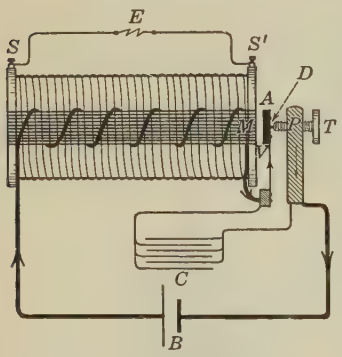


FIG. 692. — Induction coil.

When the circuit is closed, the current flowing through the primary coil magnetizes it, thus attracting the armature A and breaking the circuit at D. As the magnetic field in the primary rapidly decreases, an induced E.M.F. of high pressure is set up in the secondary coil. The core loses its magnetism, and the spring of the vibrator "makes" or closes the circuit. An induced E.M.F. of opposite direction is induced in the secondary as the magnetic flux in the primary rises to a maximum. As the vibrator alternately "makes" and "breaks" the circuit flowing in the primary, an intermittent E.M.F. is induced in the secondary. An electric spark is produced at E between the terminals, S and S', of the secondary coil.

The magnitude of the E.M.F. produced in the secondary depends: (1) upon the rate at which the magnetic field varies; (2) upon the strength of current in the primary; and, (3) upon the number of turns in the secondary as compared to the number of turns in the primary. Since the "break" of the current is so much more sudden than the "make," the induced E.M.F. is usually about 10,000 times as high when the "break" occurs.

A condenser C is almost always used with an induction coil. It is connected as in Fig. 692, so the "break" comes between its terminals. The inertia of the current gives it a tendency to follow the armature and leap across the air-gap at D as the "break" occurs. When a condenser is used, this energy surges into the condenser; the "break" becomes much more sudden, and the induced E.M.F. is increased. The spark at E is thus made thicker and longer. The condenser, immediately after the current is broken, discharges back through the primary coil. Thus it helps to demagnetize the core M.

580. Uses of the Induction Coil. Because a high voltage is induced in the secondary of an induction coil, an electric spark occurs between its terminals when they are adjusted

to the proper distance. In the automobile, the secondary coil is connected to the spark-plugs of the engine. The primary is in series with the storage battery and an automatic circuit breaker. Thus the coil produces the spark needed to explode the mixture of gasoline and air. The induction coil finds use in the *telephone*, and for the operation of *X-ray tubes*. It is also used in some so-called medical batteries.

B. TRANSFORMER AND POWER TRANSMISSION

581. The Voltage Transformer. If we connect the primary terminals of an induction coil to some source of *alternating* current, a magneto for example, an induced current is produced without the aid of a vibrator. The alternating current, in rising to a maximum in one direction and then falling to zero, varies the strength of the magnetic field around the primary, and induces an E.M.F. in the secondary. Then it rises to a maximum in the opposite direction and falls to zero, thus inducing an opposite E.M.F. in the secondary.

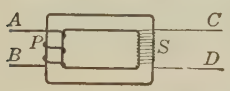


FIG. 693. — Transformer diagram.

The *voltage transformer*, which is extensively used with alternating current transmission, is a modified induction coil with the vibrator eliminated. It consists of a laminated iron ring with a few turns of heavy insulated wire wound around one section and a larger number of turns of smaller wire wound around another section. (See Fig. 693.) If we connect the terminals AB to an alternator, an induced current will be set up in the secondary coil S. The E.M.F.'s in the secondary and primary will have the same ratio as the relative number of turns of wire. Suppose we have 20 turns in the secondary for one turn in the primary, then the induced E.M.F. will be 20 times as high as that in the primary. If an alternator that gives a voltage of 110 is attached to the primary, the voltage in the secondary will be 2200.

A transformer that raises the voltage in this manner is called a *step-up transformer*. If an alternator which has an E.M.F. of 110 volts is connected to the terminals C and D, then the difference of potential between A and B is reduced to only 5 volts. Such a transformer is a *step-down transformer*.

There is no gain in energy in a transformer, because the amperage is reduced as the voltage is increased. The transformer is one of the most perfect machines ever devised. It does its work silently, with little or no attention, and with an efficiency far higher than that obtained with most machines. From 2% to 5% of the energy may be transformed into heat, so the efficiency varies from 95% to 98%. In the commercial transformer, the two coils are generally concentric. Fig. 694 shows a section of a commercial transformer. To secure better insulation and to absorb the heat, the coils are submerged in oil. Enclosed in an iron box or case, as in Fig. 695, the transformer is mounted on electric poles or it is placed in an underground compartment so animals will not be killed by coming into contact with the high voltage terminals.

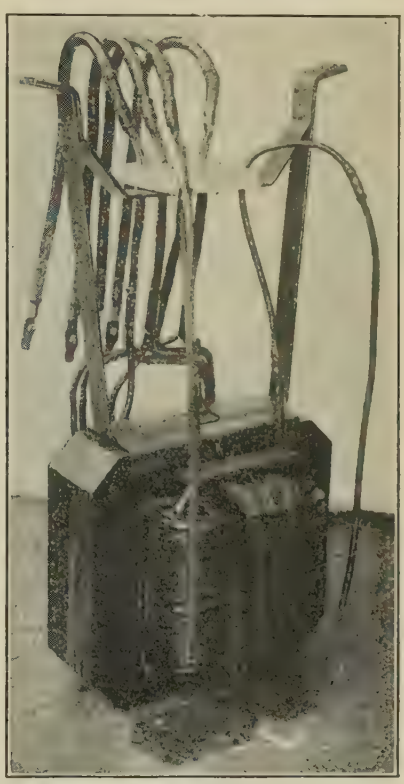


FIG. 694. — Section of transformer.

582. Transmission of Power. By the use of the nearly perfect transformer, alternating-current electricity can be transmitted long distances with much less expense than in the transmission of direct current. Suppose a company desires to transmit 1200 kilowatts of electrical energy from Niagara Falls to Syracuse, a distance of 150 miles. If it were transmitted at 12,000 volts, 100 amperes of current would be necessary. If the voltage were increased to 60,000 then only 20 amperes of current would be required. Such an arrangement is possible. The alternators at Niagara Falls generate electricity at 12,000 volts pressure; it is stepped up by a transformer to 60,000 volts and transmitted to the city in which the electricity is to be used; there it is stepped down by another transformer, or successively by several transformers, to any desired voltage. (See Fig. 696.) If this energy were transmitted at 100 amperes instead of 20, the heating effects would be 25 times as great, or $\frac{(100)^2}{(20)^2}$. Since such energy would be wasted in heating the transmission lines, there would be considerable loss. When high voltage transmission is used, much smaller wires can be used to carry the smaller current. Of course, this increases

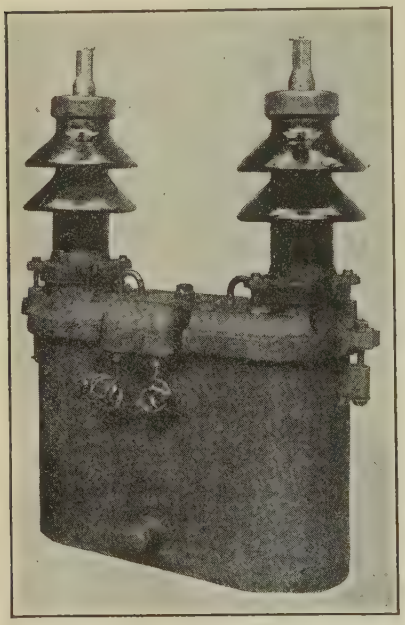


FIG. 695. — Transformer, commercial.

the resistance to some extent, but it represents a saving in the initial cost of installation and there is less stress upon the supporting towers. These insulating towers are shown

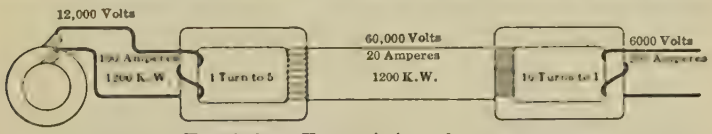


Fig. 696. — Transmission of current.

in Fig. 697. The wires are attached to the petticoat insulators, which are suspended from the tower arms. Insulators

Fig. 697. — High-tension line. Note insulators, which are of the "eight-petticoat" type.

of this type prevent to a large extent leakage from the wires through the towers to the earth.

The invention of the transformer has made the use of

alternating current practical for power transmission. The voltage of the direct current cannot be varied without tremendous losses. Hence it is customary in all distance transmission to generate current by means of an alternator, step-up the voltage by means of a transformer, and transmit the electrical energy to the distant station at high voltage.

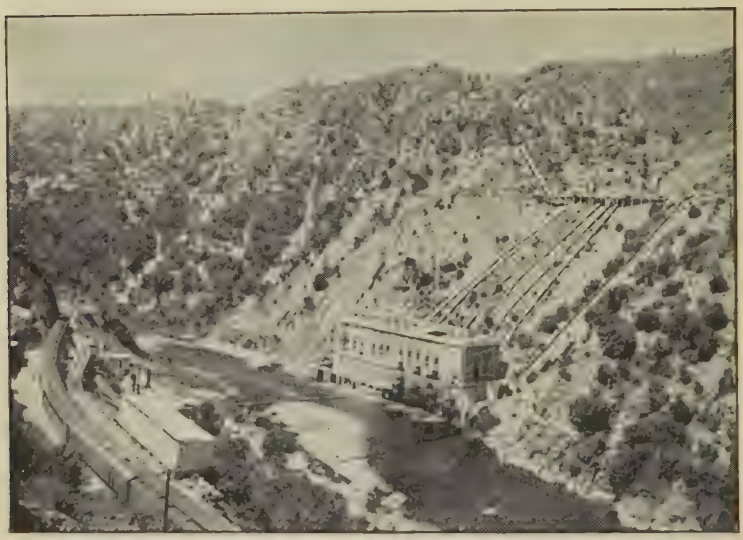


Fig. 698. — The Las Plumas hydro-electric power plant. (65,000 K.W.)

At the end of the line it is stepped down again to a safe working voltage. One high tension line now in use transmits energy at a pressure of 150,000 volts from Big Creek to Los Angeles, California, a distance of 240 miles. (See Fig. 698.)

In small towns electricity for lighting purposes is generally transmitted at 2200 volts and then stepped down to 110 volts before it enters dwelling houses or other buildings. Small transformers which step the voltage down to from 7 to 14 volts for ringing door-bells or operating Christmas-tree lights are in common use.

In cities, the cables that conduct the current of electricity are generally buried underground. Fig. 699 shows one of the methods used for insulating a power cable. The power plant of the Interborough Rapid Transit Company of New York is shown in the full-page illustration of Fig. 700. The generator is driven by steam turbines.

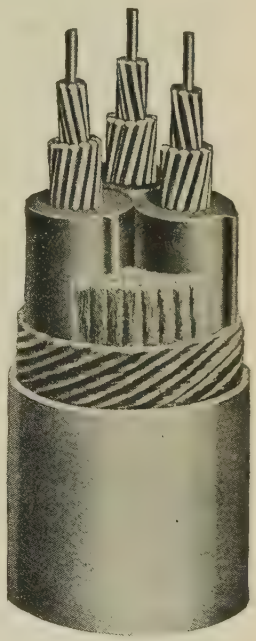


Fig. 699. — Section of insulated cable.

C. THE TELEPHONE

583. The Telephone. In the induction coil a vibrator is used to vary the strength of a magnetic field. In the transformer, this is accomplished by means of the alternating current. In the simple *telephone* the condensations and rarefactions produced by the human voice act upon a diaphragm which varies the strength of a magnetic field and produces an induced current. (See Fig. 701.) The *simple telephone* is commonly called the telephone receiver. It consists of coils of fine wire, M and M', wound around the poles of a *permanent* magnet C and C', as shown in Fig. 702. An iron disc D near the end of such a magnet is thrown into vibration by the sound waves. As this disc vibrates, it changes the direction of the lines of magnetic force, since the iron offers a better path for the lines of force than the air does. Thus the vibrating disc *varies the strength of the lines of force* of the permanent magnet as they cut across the coils of fine wire. A current is induced in the coil by these variations. When current is led into the receiver, it varies the strength of the electromagnet and causes the disc to vibrate.

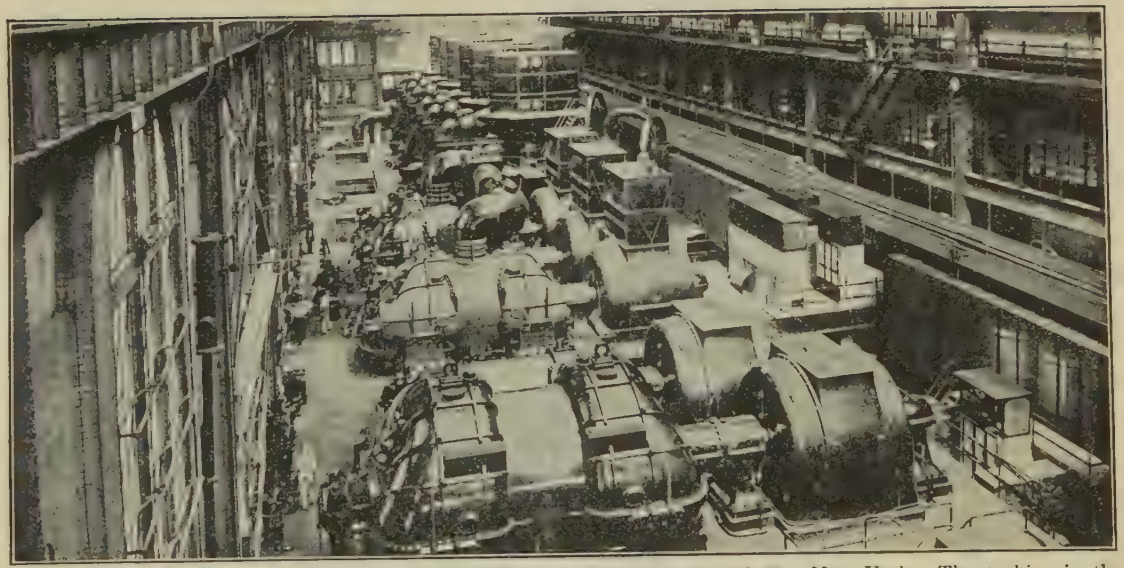


FIG. 700. — Power plant of Interborough Rapid Transit Company at 74th St., New York. The turbine in the foreground is 30,000 kilowatt. The 70,000-kilowatt turbine in the center is the largest in the world. The steam turbine is connected directly with the armature of the generator. Such a unit as the one in the center can do the work of almost 100,000 horses.

Let us ground one terminal of the coil of wire and connect the other terminal to a similar coil which is wound upon the magnet of a receiver at the other end of the line and

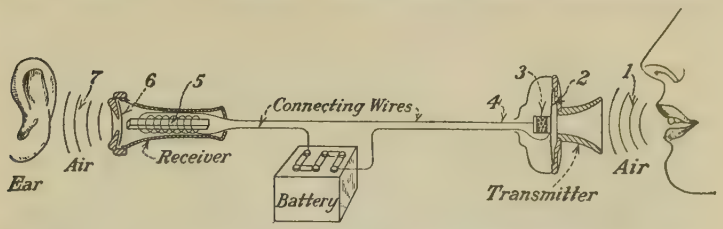


Fig. 701. — Condensations vary electric current and cause similar sound waves at receiver end. (*Courtesy Bell Telephone Laboratories.*)

then grounded as shown in Fig. 703. Now as the sound waves vary the magnetic field, the induced current set up in the coil causes the same variation in the magnetic field of the receiver at the other end of the line. Its disc will be attracted unequally by the varying current and it will reproduce the same vibrations.

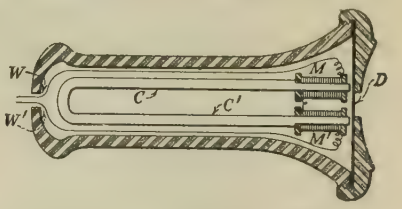


Fig. 702. — Telephone receiver.

584. The Transmitter. Since the telephone as described in the preceding section is not suitable for distances beyond a few miles, the modern telephone uses a transmitter which is much more sensitive. It consists of a small box *B*, Fig. 704, filled with particles of granular carbon. The back of the box is a fixed carbon plate attached to one terminal of a battery in series with the primary of a small transformer coil. The front of the box is a plate attached to the vibrating diaphragm, which is con-

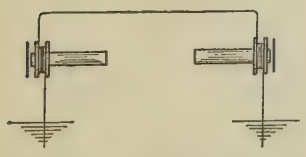


Fig. 703. — Simple telephone.

nected with the other terminal of the transformer primary. The sides of the box are made of insulating material. When a sound wave condensation presses the carbon particles closer together, their resistance becomes less, and more current flows through the primary coil. This induces a higher voltage current in the secondary. Since the receivers are connected in series with the line wire and the secondary coil, the disc of the receiver is more strongly attracted. When a rarefaction occurs, the pressure on the carbon particles becomes less and a smaller current flows through the primary coil. The variation in the resistance of the carbon particles varies the strength of the primary current and at the same time produces *corresponding* variations in the induced current in the secondary. Thus the receiver disc reproduces the same

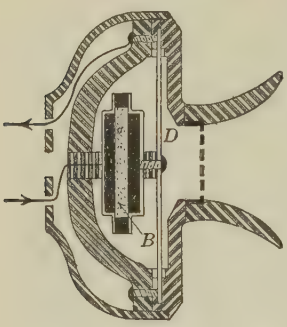


FIG. 704. — Telephone transmitter.

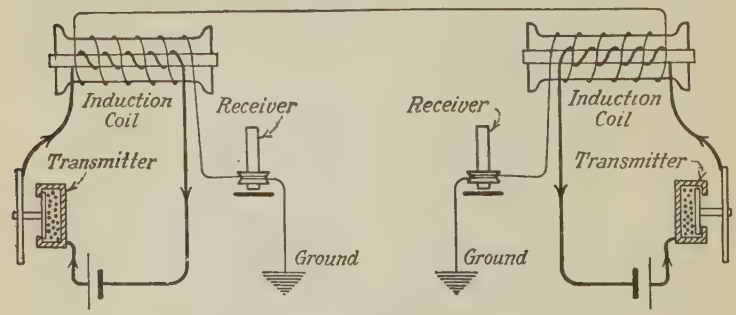


FIG. 705. — Local telephone system.

vibrations as those impressed upon the disc of the transmitter. Fig. 705 shows a local-battery telephone system. Sometimes only one wire is used, the other being grounded

as shown by the dotted lines. In the vicinity of trolley lines or electric lighting circuits, two wires must be used to prevent induction from stray earth currents. The use of two wires largely eliminates confusing noises from cross-circuits. On long distance lines the current may be too weak to enable us to hear distinctly. Vacuum tubes called repeaters, Fig. 706, are used to amplify the feeble current. Fig. 707 shows a section of lead cable used for laying telephone wires in conduits. A few years ago the anchor of a vessel in New York harbor dragged a cable of this type. Try to imagine the difficulty involved in untangling such a network of wires.

FIG. 706. — A vacuum tube used as a "repeater" tube on long distance telephone lines.

585. The Audiphone. The invention of permalloy, which contains about 80% nickel and 20% iron, made possible the development of the *audiphone*. A plaster mold is first made to fit the ear of the person whose hearing is impaired. Then a small hard-rubber earpiece is made from the plaster mold. The light, efficient audiphone receiver can then be attached to the earpiece. A carbon microphone, shown in Fig. 708 attached to the wearer's pocket, a battery, and a vacuum-tube amplifier make the equipment complete. The audiphone is light and it fits the ear perfectly. Since it is practically free from distortion, it is a boon to those whose hearing is defective.

D. SELF-INDUCTION

586. Self-Induction. Let us connect two dry cells in series and then connect one of the terminals to a piece of

FIG. 707. — Telephone cable, 2¾ in. in diameter. This cable contains 1200 pairs of No. 24 B. & S. gauge copper wire, insulated with strips of paper.

wire gauze or to a coarse steel file. If a wire connected to the other battery terminal is then drawn across the gauze or the file, a few feeble sparks are produced. If we repeat the experiment after an electro-magnet has been connected in series in the circuit, the sparks that are emitted are much

longer and thicker than before. The coils of the magnet have given the effect of adding *extra current.*

Since a current in a primary coil induces current in a secondary coil surrounding it, it seems reasonable to suspect that just as soon as the current begins to flow in *one loop* of a coil, it will induce current in the *adjacent loops of the same coil.* This phenomenon, which was discovered by an American, Joseph Henry, is called *self-induction.* Of course this self-induction produces an E.M.F. that opposes the current. When the circuit is broken, self-induction opposes the "dying out" of a current. It is closely akin to inertia in mechanics. The so-called *extra current* added to the *inducing* current causes the "fattening" of the spark when the circuit is broken.

FIG. 708. —The audiphone.

Self-induction occurs with *direct* current only at the "make" and "break" of the circuit. With *alternating* current, it is always present. Of course it does not occur in straight wires, but in coiled spirals only. Coils of wire in an alternating circuit have a "choking" effect upon the current on account of self-induction.

A spark-coil consists of a large number of turns of insulated copper wire wound on an iron core. If such a coil is connected with two or three cells in series, a large spark is produced when the current is broken. Such a coil may be used for lighting gas-jets or for ignition purposes.

E. ALTERNATING CURRENT POWER

587. Alternating Current Power. In an alternating circuit, *self-induction* always occurs. By its opposition to the flow of the current, it produces a retarding effect so that the current in an alternating circuit *lags* behind the E.M.F. Fig. 709 shows both the voltage and amperage curves of an alternating circuit. The current does not reach its maximum so quickly as the voltage does, but it *lags* behind the voltage.

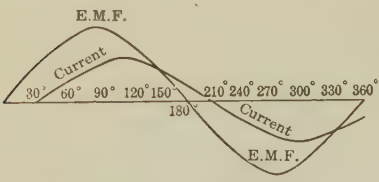


FIG. 709. — Lag curves.

Because the current and voltage do not reach their maximums at the same time, we cannot find the power of an alternating circuit by multiplying volts times amperes as in the case with direct current. We must multiply *volts times amperes by some power factor*. The factor to be used will vary with the individual circuit, but it is always less than one. Therefore the *apparent wattage* of an alternating circuit is always more than the *actual wattage*.

588. Reactance and Impedance. We have already learned that self-induction occurring at each alternation produces the same effect on the current flow in an alternating circuit as a high resistance, but it does not produce the heat effects. Self-induction in such cases is known as *reactance*. When a coil is placed in an alternating circuit, it reduces the flow of current by both *resistance* and *reactance*. The combined effect of both factors is called *impedance*, which we may represent by the letter Z. If we use the reactance and resistance as sides of a right triangle, the impedance is mathematically equal to the hypotenuse of the triangle. (See Fig. 710.) In dealing with alternating currents,

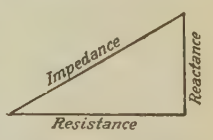


FIG. 710. — Impedance as related to resistance and reactance.

Ohm's law must be modified to include both resistance and reactance. We substitute impedance for resistance as follows:

$$\text{current} = \frac{\text{voltage}}{\text{impedance}}; \text{ or, } I = \frac{E}{Z}.$$

589. The Choke Coil. Sometimes a coil of wire of many turns, but of low resistance, is introduced into an alternating circuit to reduce the amount of current. Such a coil is called a "choke coil." Suppose such a coil has a resistance of only 4 ohms, and an impedance of 240 ohms. If it were connected to a 120-volt direct current, 30 amperes of current would flow through the circuit. When this coil is connected to a 120-volt alternating circuit, only 0.5 ampere of current will flow through the circuit. Fig. 711 shows a "choke coil" connected in circuit with several lamps. When an iron core is introduced into the coil, the reactance is increased decidedly, and the lamps are dimmed. Coils of *varying reactance* are much used in alternating circuits.

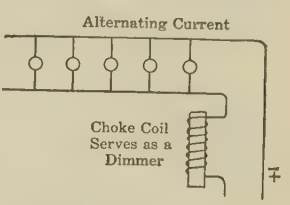


FIG. 711. — Choke coil.

F. CURRENT RECTIFIERS

590. How Alternating Current is Changed to Direct Current. In villages and small cities alternating current is used extensively for lighting purposes. Very often it is the only current available. For charging storage batteries and for some other purposes direct current must be used. There are several methods in use for changing alternating to direct current. Devices used for this purpose are often called current transformers.

The *motor-generator* is a simple device sometimes used to change or transform alternating to direct current. It consists of an alternating-current motor and a direct-current

dynamo, both mounted on the same shaft. The motor uses alternating current to turn the dynamo, which generates direct current.

The *rotary-converter* is often used to convert alternating current into direct current for street-car motors. The small brick buildings frequently seen between the villages along an inter-urban line are rotary converter sub-stations. The alternating current from a high-tension line enters the armature of the converter at one end of the shaft over slip-rings and turns the armature as a motor. Direct current is taken from the other end of the armature by means of a commutator, whence it is supplied to the trolley wire directly.

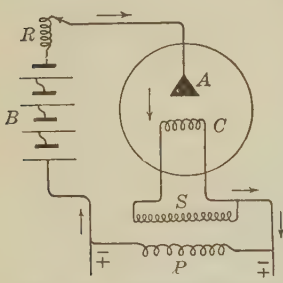


Fig. 712. — Tungar rectifier.

The *tungar rectifier* is also used for charging storage batteries. It consists of a bulb filled with argon gas at reduced pressure. The cathode C is a coil of tungsten wire and the anode A is a small cone of graphite or tungsten. (See Fig. 712.) When the anode has a potential several volts higher than the cathode, electrons are discharged from the cathode if it is highly heated. These electrons split the argon molecules into positive and negative ions which conduct the current through the bulb. The cathode is heated by the alternating current which is so connected with the bulb that the anode A and the cathode C are alternately $(+)$ and $(-)$. Electrons are discharged only when the cathode is $(-)$. When the anode is $(-)$ no molecules are ionized. Therefore the alternating current is changed into a *pulsating* current flowing in one direction only.

Nodon valve. The electrolytic rectifier, or Nodon valve, is quite satisfactory, and it can be made at little expense. This rectifier consists of a plate or rod of aluminum and one

of lead immersed in a jar containing a saturated solution of baking soda, ammonium phosphate, or borax. When the current is turned on, oxygen and hydrogen gases are liberated. These gases unite with the aluminum to form a layer of aluminum hydroxide on the surface of the aluminum plate. This hydroxide layer acts as a valve, permitting current to flow from the lead to the aluminum, but not in the opposite direction. Thus the alternating current is changed into a direct current.

SUMMARY

An induced E.M.F. is produced by varying the strength of the magnetic field in which the conductor is placed. The magnetic field may be varied by the use of the "make" and "break"; by an alternating current; or by an iron disc moving in the magnetic field, as with the simple telephone.

The induction coil is used for ignition purposes in gas engines, for medical batteries, for X-ray work, and for wireless.

The voltage transformer raises or lowers the voltage of an alternating current. A step-up transformer raises the voltage; a step-down transformer lowers the voltage.

Ohm's law does not apply directly to alternating currents, since they are influenced so much by reactance or self-induction.

Alternating currents may be converted into direct currents by motor generators, rotary converters, or tungar rectifiers.

QUESTIONS

1. Outline as many methods as you can for producing an induced E.M.F.

2. How does an induced E.M.F. differ from an induced current?

3. Draw a diagram to show how gas-jets could be connected with a coil and battery to make them self-lighting.

4. Can you see any reasons for using oil in voltage transformers?

5. Eddy currents in the "former" of a galvanometer coil prevent vibrations and bring the coil to rest quickly. Such a galvanometer is called "dead-beat." Explain the action.

6. Why are the coils of a rheostat wound back upon themselves as in Fig. 637?

7. Summarize the advantages of the alternating current. Summarize the advantages of the direct current.

8. From the principle of self-induction explain why a shunt-wound motor will not run on an alternating current, while a series-wound motor will run on either direct current or alternating current.

9. A coil of wire is introduced into an electrical circuit. Will the coil be heated more highly if the current is direct or alternating, provided the voltage is the same? Explain.

10. Why is some type of rectifier necessary for use with a radio set?

CHAPTER 28

RADIO—X-RAYS—RADIO-ACTIVITY

Vocabulary

Kilo-cycle, 1000 cycles or revolutions per second.
Radio-frequency, having a frequency of more than 10,000 cycles per second; producing waves to which the ear is not sensitive.
Audio-frequency, having a frequency of less than 10,000 cycles per second; producing waves to which the ear is sensitive.
Transmutation, the changing of one element into another.

A. RADIO

591. Introductory. Very few important inventions have come as the result of a sudden inspiration, and few have been the fruit of the labors of any one man. Communication by wireless is no exception. In 1873, James Clerk-Maxwell published his treatise on *Electricity and Magnetism*, in which he affirmed that electricity and light have the same nature, and that both are propagated by means of ether waves in the same manner and at the same speed. Fifteen years later, Heinrich Hertz detected these electric waves and measured their length. He also showed that they can be refracted and reflected just as in the case of light waves. In 1894, Marconi devised the *coherer* and made practical the sending of wireless signals. The waves are usually called Hertzian waves, and Marconi is generally credited with being the pioneer in wireless communication.

In the study of radio as we know it today, we shall also have occasion to refer to Edison, J. J. Thomson, Fleming, De Forest, and Armstrong. Many others have contributed bits here and there toward the successful development of this science.

592. Transmitters, Some Medium, and Receivers Are Needed. In our study of sound we learned that sound has its origin in the vibration of matter; its waves travel through air or some other medium; and our ear serves as a receiver. Light waves are similar, but we assume that they travel to our eye through an imaginary fluid which we call the ether. In radio we need some apparatus to produce radio waves; we generally assume that these waves are ether waves; and some device must be used to detect the presence of such waves. In the following section we find that the effect these ether waves produce seems to depend upon their length.

593. Different Types of Ether Waves. Sound waves are not ether waves, but they travel through ordinary matter. Light waves and radio waves are *believed to be ether waves.* Let us refer to Fig. 713, which pictures the effects of the so-called ether waves of varying length. The *radio waves* are long, varying from 10 meters to more than 10,000 meters. Heat waves are very short, but *light waves* are still shorter. It would need about 200 light waves laid end to end to equal the thickness of this sheet of paper. But a photographic plate is darkened rapidly when it is held in a solar spectrum *beyond* the violet light waves, which are the shortest that are capable of affecting the eye. These *ultra-violet waves* are much shorter than light waves; some of them are less than $\frac{1}{30}$ of the length of those waves which produce the sensation of violet light. But the smoothest surface, which may not vary more than one-millionth of an inch, is rough enough to scatter the exceedingly short *X-rays.* It is estimated that it would take 300,000,000 of the shortest X-rays to make a line an inch long. Certain shorter rays are also known. Recently they were investigated and measured by Robert A. Millikan. These *cosmic rays* are probably not nore than $\frac{1}{500}$ as long as the shortest X-rays. The cosmic, or Millikan rays, seem to enter the earth from all space. They are the most penetrating rays known.

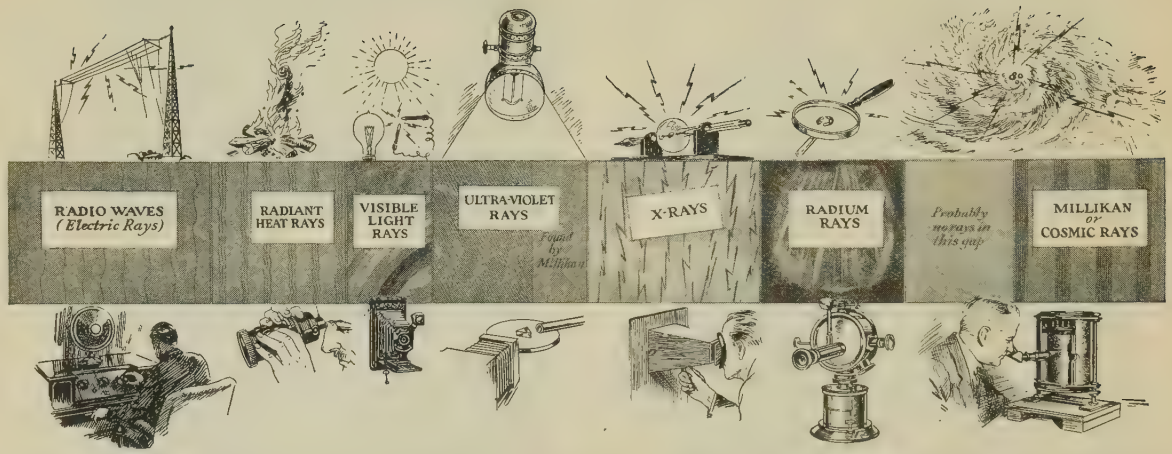


FIG. 713. — These drawings show the effect that the ether waves of different lengths produce, and the manner in which they are produced. The student will observe at least one gap. Our senses can not detect any waves here, and no instrument that has been devised can detect them, even if they exist. (*Courtesy of Popular Science Monthly.*)

Sir William Crookes.

Crookes' tube. Methods of producing high vacua.

Wilhelm Konrad Roentgen.

Discoverer of X-rays.

Heinrich Rudolf Hertz.

Discoverer of Hertzian waves.

Guglielmo Marconi.

Inventor of wireless telegraph.

594. Velocity and Frequency of Radio Waves. Since radio waves have the same velocity as light waves, they travel 186,000 miles per second. In the Metric system, this is equal to 300,000,000 meters per second. Suppose we have a generator which is sending out 1,000,000 of these waves per second. At the end of one second we shall have 1,000,000 waves spread over a length of 300,000,000 meters. Of course they are 300 meters apart. We say the wave length is 300 meters. In our study of sound, we used the formula $v = nl$. See § 324. We may use the same formula to find either the *wave length* or the *frequency* of radio waves, since we know their *velocity*. For example, a station broadcasting on a frequency of 1,000,000 cycles per second will send out waves 300 meters long ($300{,}000{,}000 \div 1{,}000{,}000 = 300$). Such a station is rated at 1000 *kilo-cycles*, since there are 1000 cycles in a kilo-cycle. To produce waves 400 meters long, a station must send out 750,000 waves per second. According to the rules of the Federal Radio Commission each licensed broadcasting station must use an assigned wave length and no other.

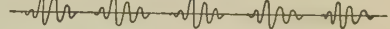


FIG. 714. — Damped waves.

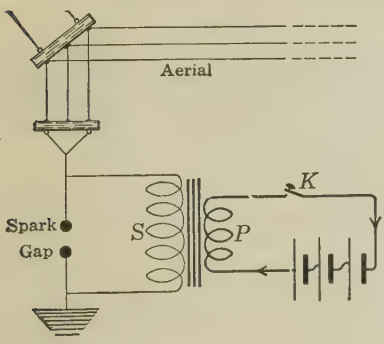


FIG. 715.—Transmitting system, wireless.

595. How Radio Waves May Be Produced. There are many ways in which radio waves may be produced. The electric spark caused when a static machine or an induction coil is in operation produces radio waves. Such a spark oscillates rapidly. It sends out *damped waves* of the type shown in Fig. 714. Such waves are suitable for sending signals, but they

are not satisfactory for broadcasting the voice or music. A *continuous carrier* wave must be produced for this purpose.

Fig. 715 shows how an induction coil can be used to send out radio waves. A contact key K is connected in series with a battery and the *primary* of the coil. One terminal of the *secondary* is grounded and the other terminal is con-

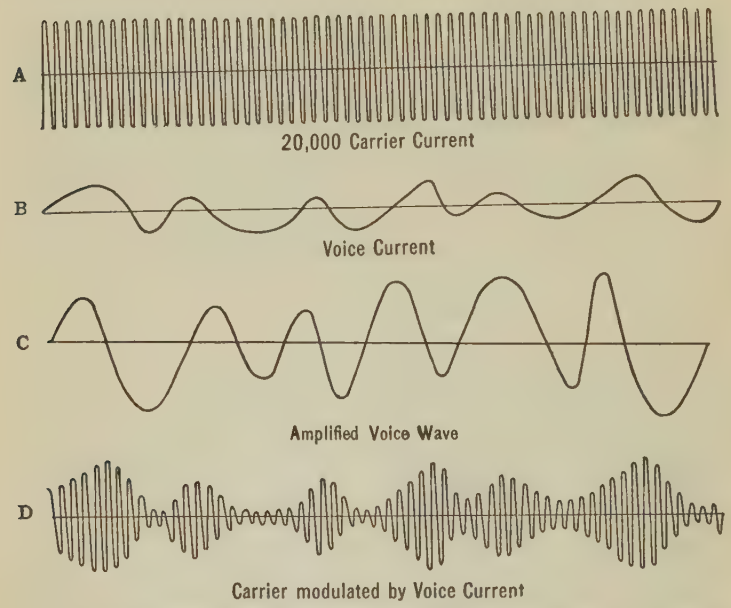


FIG. 716.—*A*. Carrier Wave. *B*. Voice Wave. *C*. Amplified Wave. *D*. Carrier Wave modulated by voice wave.

nected to an aërial system. When the key is pressed, a train of damped waves is sent out from the aërial. A short train of such waves corresponds to a "dot" in the Morse code and a longer train to a "dash."

The continuous wave needed as a carrier wave for use in wireless telephony may be produced by means of the Poulsen arc, or a high-frequency alternator. Such a generator,

which was devised by Alexanderson, uses a rotor which makes thousands of revolutions per minute. The continuous wave is now generally produced by a three-electrode vacuum tube, which serves as an oscillation generator. The frequency at which it oscillates is controlled by the use of inductance and capacity.

596. How the Voice Is Put on the Air. The audion tube, which will be more fully described in § 597 serves three purposes in broadcasting: 1. Such a tube produces the high-

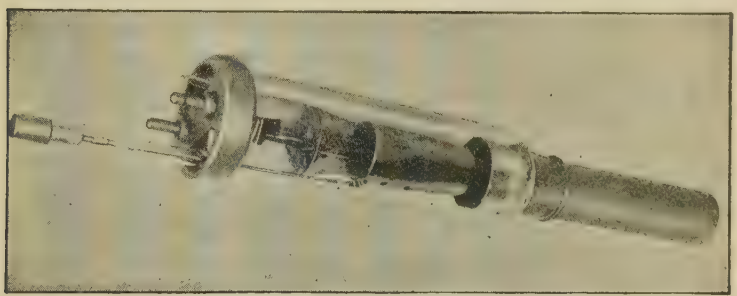


FIG. 717.— Water-cooled 50 kilowatt experimental tube used as amplifier. (*Courtesy of Bell Telephone Laboratories.*)

frequency waves, which serve as *undamped carrier waves.* (See Fig. 716*A*.) Their frequency is too high to affect the human ear, and they are known as *radio-frequency waves.* 2. Another audion tube serves as a *modulator.* It blends or unites the *voice wave,* which is capable of affecting the auditory nerve, with the carrier wave. The voice waves, as shown in Figs. 716*B* and 716*C*, are *audio-frequency waves.* Fig. 716*D* shows one form of *modulated wave.* 3. A bank of audion tubes is then used to *amplify* the modulated wave. Sometimes the voice wave is amplified before modulation occurs. (See Fig. 716*C*.) These audion tubes are similar to the vacuum tubes used in receiving sets, but they are much larger. Some have an output of 50 kilowatts, or nearly 70 horse power. (See Fig. 717.)

The diagram of Fig. 718 shows how audion tubes are used to put the voice on the air. When one talks or sings, condensations and rarefactions of the air are produced. These air-waves cause variations in the primary circuit of the telephone transmitter or the microphone. Corresponding E.M.F.'s are thus induced in the secondary, which causes changes in the potential of the grid of the modulator

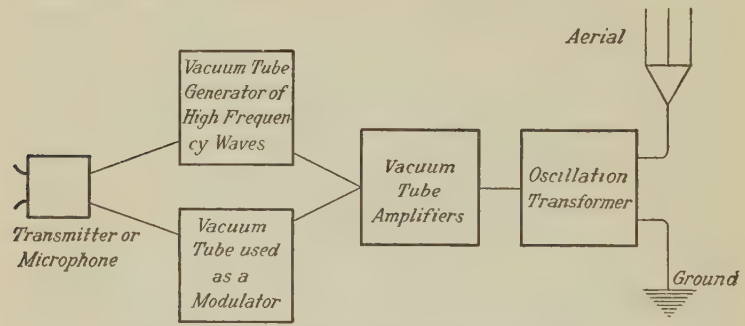


Fig. 718. — Diagram to show how voice is put on the air.

vacuum tube. After the modulated wave has been amplified, it goes through an oscillation transformer to the transmitting aërial.

597. How Radio Waves are Received. Just as several methods of producing radio waves are or have been used, so several kinds of *detectors* have been used during the development of radio. Although the audion tube is now almost exclusively used for reception, yet it may be of interest to study briefly the coherer and the crystal detectors, which are now practically obsolete. When the waves which were sent out in all directions, as discussed in the preceding section, meet a receiving aërial, they *induce* in it currents of electricity. This induced current will be feeble, but it will have the same frequency and form as the transmitted waves.

1. *Coherer.* Marconi devised a coherer which was capable of detecting the damped waves used for signaling. It con-

sists of a tube containing a mixture of metal filings as shown in Fig. 719. Two metal plugs are shoved into the tube until they make contact with the filings. These two plugs are connected in series with a battery and a relay, which acts as a circuit closer for a telegraph sounder. (See § 518.) Normally the filings offer so much resistance that the battery current is too feeble to close the relay. But the Hertzian waves, when they come into contact with the filings, cause them to cohere, or stick together. Such cohesion of the filings reduces their resistance, and enough current flows through them to operate the relay. Thus the circuit is closed by the relay and a signal is produced by the sounder. Marconi found that after the signal was produced, the coherer had to be tapped slightly to jar the filings apart so they would be ready for the next signal.

Fig. 719. — Coherer.

2. *Crystal detectors.* At one time crystals were extensively used by amateurs as detectors of Hertzian or radio waves. One of the best was galena, one of the ores of lead. Such a

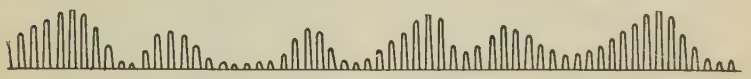


Fig. 720. — Pulsating direct current wave.

crystal has the ability to transmit current in *one* direction readily, but it offers great resistance to the flow of current in the *opposite* direction. Hence such a crystal can change an alternating current into a direct current. Thus the alternating current becomes a *pulsating*, direct current.

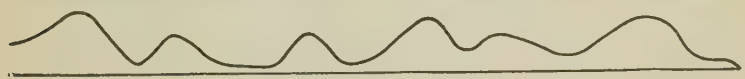


Fig. 721. — How receiver produces audio-frequency waves, from Fig. 720.

See Fig. 720, which shows the effect that the crystal produces upon the modulated wave. These pulsations combine in groups to form waves of lower frequency. (See Fig. 721.)

Thus the incoming radio-frequency waves, which have such a high frequency that the diaphragm of the ear-phones cannot respond to them, are changed into audio-frequency waves, to which the ear is sensitive. Fig. 722 shows a simple receiving set of the crystal type. B is a variable inductance coil connected with the aërial-ground system. B' is balanced with B by varying its inductance and by means of condensers. D is the crystal detector.

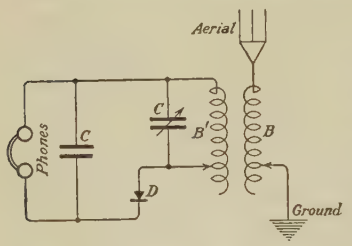


Fig. 722.— Crystal as a detector.

3. *The audion tube.* We have already learned that the audion tube, Fig. 723, is the heart of the transmitting station. It is just as important in the receiving set. Its development is interesting. A few years after Edison invented the incandescent lamp, in 1883, he experimented with a two-electrode bulb like that shown in Fig. 724. He found that current would flow through the galvanometer, but he could not explain how the current could flow from the hot filament to the plate. No one knew about electrons, and the experiment, which was known as the *Edison effect*, was temporarily forgotten.

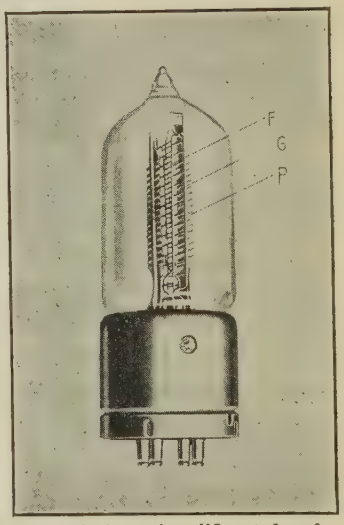


Fig. 723. — Amplifier tube, for receiving. F, filament; G, grid; P, plate.

Now that J. J. Thomson has given us the electron theory, the explanation is easy. We know that electrons are ex-

pelled from a hot filament. Some of them are attracted to the metal plate.

More than twenty years later, Fleming discovered that current will flow through a galvanometer connected with a plate in a two-electrode tube or bulb, *provided the plate is charged positively.* See Fig. 725, which shows how the current flows to the plate when it carries a positive charge. No current flows when the plate carries a negative charge. We can increase the amount of current flowing through the galvanometer in two ways. If we reduce the resistance in the filament circuit, more current will flow through the filament, and its temperature will be increased. At the higher temperature, more electrons are pushed out of the filament. If we increase the plus voltage on the plate, it will attract the electrons more readily. Fleming used such a tube for changing alternating current in the filament circuit into direct current in the plate circuit. His device, which was called the *Fleming valve*, was used for charging storage batteries.

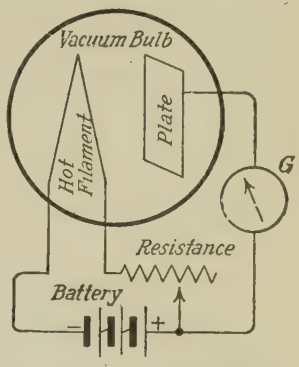


FIG. 724. - - Edison effect.

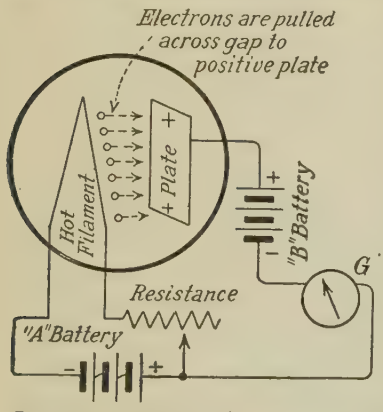


FIG. 725. — Positive charge on plate "pulls" electrons.

It was the work of Lee De Forest that made the audion tube the modern miracle that it is today. J. J. Thomson's theory affords an easy

explanation of the Edison effect, but De Forest invented a device to control the flow of electrons. He introduced a third electrode, or *grid*, between the filament and the plate of the two-electrode tube. Let us refer to Fig. 726 to help us understand what the grid really does. We have already learned that the electrons flow from the filament to the plate when the plate carries a positive charge. If the plate is *kept* positively charged and the grid is placed between

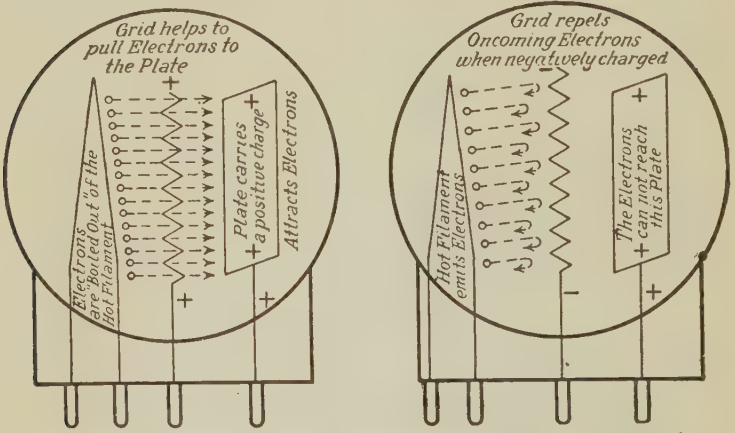

Grid helps to pull Electrons to the Plate
Electrons are Boiled Out of the Hot Filament
Plate carries a positive charge
Attracts Electrons
Grid repels Oncoming Electrons when negatively charged
Hot Filament emits Electrons
The Electrons can not reach this Plate

Fig. 726. — How grid controls the flow of current in the plate circuit.

the filament and the plate, it can be made to act as a valve to control the flow of the electrons. The grid acts like a traffic policeman at the entrance to a one-way street. When his gesture is positive, traffic moves; it halts when his signal is negative. When the grid is positively charged, it helps to attract or "pull" the oncoming electrons. When the grid is negatively charged, it repels or "pushes" the electrons so that few or none of them reach the plate. Thus even a feeble alternating current applied to the grid can control a powerful current in the plate circuit. The alternating current charges the grid positively and then

negatively. Only the upper half of the modulated wave of Fig. 716 passes the grid of this vacuum valve known as the *audion tube.* (Refer to Fig. 720.)

598. The Standard Receiving Set. We are now ready to study the action of a standard single tube receiving set. If we refer to Fig. 727, it will be easy to understand exactly what each part of the receiving set is designed to accomplish.

1. *The "A" battery.* In order to *heat* the filament of the audion tube, a storage battery of from 2 to 6 volts is generally

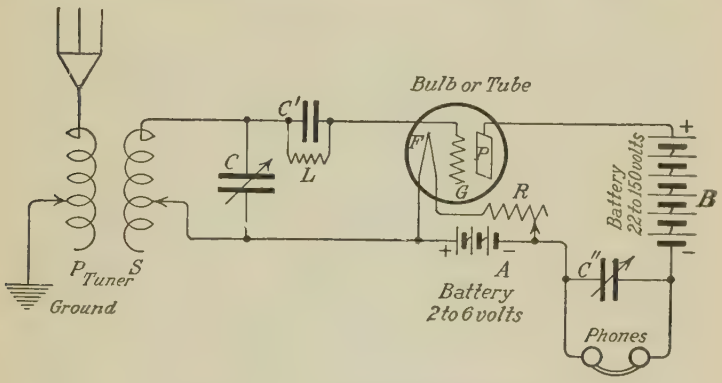


FIG. 727. — Standard receiving set.

used. It is connected in series with a rheostat R so that the amount of current flowing through the filament may be varied. Electrons are driven out of the hot filament. Increasing the temperature by cutting out resistance increases the number of electrons "boiled out" of the filament, but the life of the tube is shortened by an excess of current. The *filament circuit* includes the filament, the "A" battery, and a coil of variable resistance.

2. *The "B" battery.* The positive terminal of the "B" battery, which supplies from 22 to more than 100 volts, is always connected to the *plate* of the audion tube. Thus it keeps the plate charged *positively* at all times. The other

terminal of the battery is connected in series with the ear phones or the loud speaker and one terminal of the "A" battery. If we increase the voltage on the plate, more electrons will be pulled over to the plate. Hence we can increase the flow of electrons in the plate circuit by increasing the plate voltage or by raising the temperature of the filament. A cold filament does not emit electrons. The *plate circuit* includes the plate, the "B" battery, the ear phones or the loud speaker, and the filament with its stream of electrons through the audion tube.

3. *The grid circuit.* As the radio waves come from the broadcasting station, they induce in the aërial high frequency currents. These radio-frequency currents induce currents of the same frequency in the grid circuit; thus the grid acquires positive and negative charges in turn. In the preceding section we learned how the grid changes *radio-frequency* currents into *pulsating* currents flowing in one direction. This pulsating wave causes the diaphragm of your loud speaker to vibrate and produce condensations and rarefactions of the same nature as those impressed upon the microphone. The student will observe that the grid is connected with the aërial so that it will always be influenced by the radio-frequency waves induced in the antenna. Sometimes electrons accumulate on the grid and interfere with its action. A grid leak L is connected across the terminals of a condenser in the grid circuit. It consists of an exceedingly high resistance, rated in *megohms*, or millions of ohms.

599. The Principle of Tuning. In our study of sound, we learned that one tuning fork held in one part of a room will throw another tuning fork some distance away into sympathetic vibration, provided both forks have the same frequency. (See § 336.) Each *succeeding* condensation of the sound wave from the first fork impinges upon the second fork and finally causes it to vibrate. The principle of

tuning in radio is similar to sympathetic vibrations caused by sound waves. When a high-frequency Hertzian wave strikes your aërial, it induces a current in your receiving set. If the wave makes the circuit through your set and back to the aërial by the time the next wave arrives, each succeeding wave will help to build up the current flowing through the set. If the wave makes the circuit of your set more slowly or more quickly than the appearance of the next wave, interference will result. The waves thus tend to destroy one another.

Condensers and *inductance coils* are used in tuning receiving sets. In § 586 we learned that a current flowing through one turn of a spiral coil induces current in an adjacent coil. (Self-induction.) In the *tuner* of Fig. 727 it is possible to vary the *inductance* of the primary or the secondary coil by means of a sliding conductor which may make contact with the various loops of the coils as shown by the arrows. Varying the distance between the two coils also varies the *inductance.* Increasing the inductance in the circuit of your set increases the wave length to which it is attuned. The antenna has a natural wave length depending upon its length, but such a natural wave length may be changed by inductance coils. The *henry* is the unit of inductance. A circuit has an inductance of one henry when an inducing current which varies at the rate of one ampere per second causes an induced pressure of 1 volt. The *millihenry* or the *milhenry* is more commonly used in wireless work. It is one thousandth of the henry. The *milhenry* equals 1000 *micro-henries.*

Both *fixed and variable condensers* (see § 486) are used in radio reception. The *capacity* of condensers is measured in *farads.* A condenser has a capacity of one farad, if it gives a pressure of one volt when charged with one coulomb of electricity. The *coulomb* is the unit of electrical quantity; it is the amount of electricity or the number of electrons

transferred by a current of one ampere flowing for one second. Since the farad is an extremely large unit, the *micro-farad*, which is one-millionth of the farad, is used as a capacity unit in wireless work. In tuning your set, increasing the capacity of the condenser increases the wave length to which your set responds. Thus we find that both inductance coils and

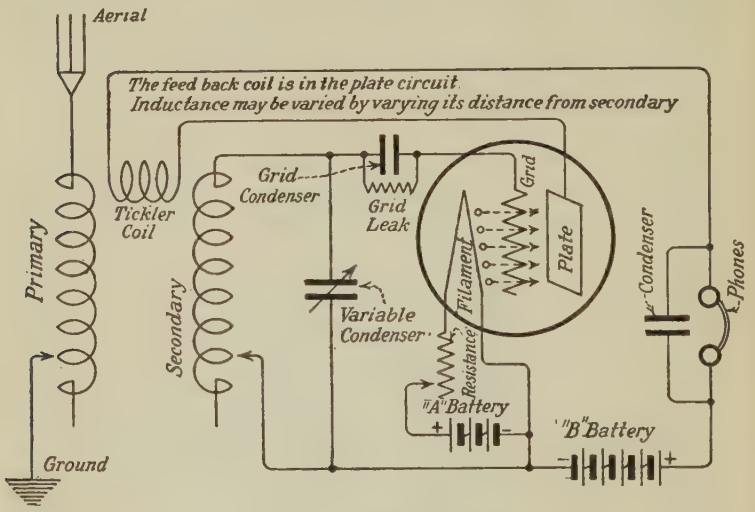


Fig. 728. — Regenerative circuit.

condensers are used in tuning, or in producing *electrical resonance*.

600. The Regenerative Principle. The oscillating current in the tuned grid circuit causes feeble oscillations to be set up in the plate circuit. In the use of the *regenerative* principle, these very feeble oscillating currents in the plate circuit are fed back to the grid circuit through a *tickler coil*, which is mounted close to the grid coil. (See Fig. 728.) By induction this current in the tickler coil increases the current in the grid circuit. The voltage is increased since the induced voltage from the tickler coil is added to that induced by the

incoming radio waves. Such a regenerative circuit may build up high enough voltage to make the tube oscillate, or squeal. A squealing tube becomes a transmitter and sends out radio waves that may interfere with reception by other sets in the neighborhood.

601. How Additional Vacuum Tubes Produce Amplification. In our study of the method of producing radio waves, we learned that the vacuum tube may serve as a *generator* of radio waves, as an *amplifier*, or as a *modulator*. In our receiving sets we use these tubes as *detectors* and as *amplifiers*. When vacuum tubes are used as amplifiers, they may

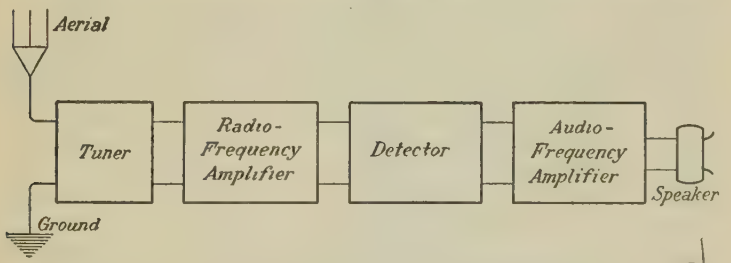


FIG. 729. — Diagram to show amplification.

be so connected that they will amplify the radio-frequency waves before they enter the detector. They are also used to amplify the audio-frequency waves as they come from the detector. The scheme used may be illustrated by the diagram of Fig. 729. From the aërial the radio-frequency waves go to the tuner; by means of one or more audion tubes they are amplified; then an audion tube serves as a detector and changes the high frequency waves into pulsating audio-frequency waves. One or more audion tubes may then be used to amplify the audio-frequency waves before they reach the loud speaker. Thus the volume of sound is intensified. (See Fig. 730.)

To secure *amplification of the radio-frequency waves*, the plate circuit of the first audion tube does not contain the

loud speaker. Instead the *primary* of a step-up transformer is connected to this plate circuit. The *secondary* of this transformer is connected with the grid of the detector tube. The transformer steps-up the voltage in the secondary. Thus the current is strengthened and the detector tube will respond to more feeble waves from more distant stations. One, two, or more tubes may be used in this manner to produce different *stages* of amplification. Usually a variable

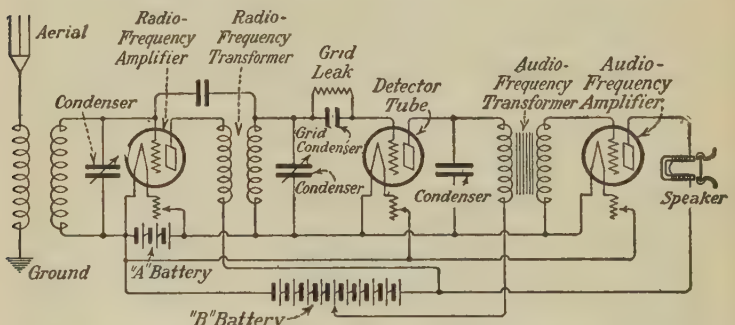


FIG. 730. — One stage of radio-frequency amplification and one of audio-frequency.

condenser is used with the transformer in the amplifying circuit to permit the tuning of this circuit. (See Fig. 730.)

The *audio-frequency waves may also be amplified* as they come from the plate circuit of the detector. Here again the plate is connected in series with the primary coil of a transformer. The secondary of the transformer, which is connected to the grid of the next tube, steps up the voltage in the circuit. We have already seen how the grid controls the amount of current in the plate circuit. As the voltage on the grid is increased, it will pull more electrons from the filament when it carries a plus charge, and repel more strongly when it is negatively charged. Thus more current will flow in the plate circuit of the amplifying tube. One or more *stages* of audio-frequency amplification may be used. The

loud speaker is placed in the plate circuit of the last amplifier. The *loud speaker* is similar to the telephone in its construction. Its electro-magnet controls a diaphragm which yields condensations and rarefactions like those produced in the microphone. It also has a resonating horn to augment these waves.

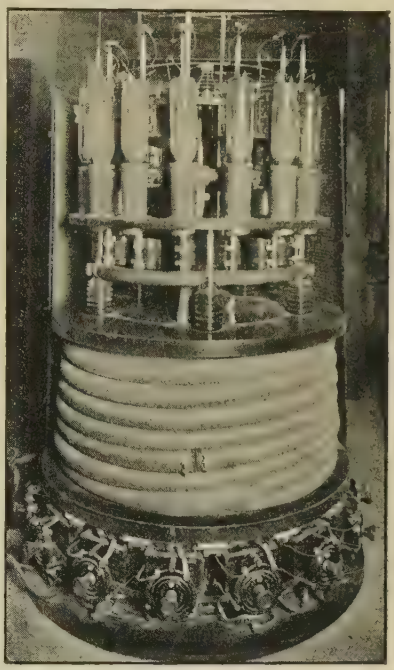


FIG. 731.— Bank of water-cooled amplifiers used at Rocky Point, Long Island. (*Courtesy of Bell Telephone Laboratories.*)

602. The Trans-Atlantic Radio Telephone. Since January 7, 1927, it has been possible to converse between New York and London. You do not drop a nickel in the slot, but you pay $45 for a 3-minute conversation with your friend in London. Part of the service is over the land telephone and part by wireless. From your own phone your voice goes to the Central Station of the American Telephone and Telegraph Company in New York. Then it travels by wire to Rocky Point, Long Island. Here it is amplified by twenty-three vacuum tubes, each about two feet long. It is amplified 2,000,000,000 times and sent across the Atlantic Ocean on a wave length of 5000 meters. (See Fig. 731.) One writer says, "The 70-horse power voice with which we shout electrically across the ocean has the collective speaking power of about 2,000,000,000 people, nearly the population of the earth." But when your voice reaches

Wroughton, England, it is 1000 times fainter than it was when it left your phone. "Our 70-horse power voice has dwindled to something inconceivably fainter than the in-

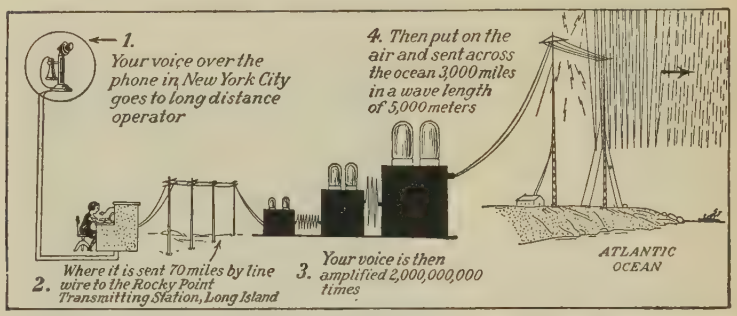

1. Your voice over the phone in New York City goes to long distance operator
2. Where it is sent 70 miles by line wire to the Rocky Point Transmitting Station, Long Island
3. Your voice is then amplified 2,000,000,000 times
4. Then put on the air and sent across the ocean 3,000 miles in a wave length of 5,000 meters
ATLANTIC OCEAN

FIG. 732. — How one talks with London.

audible whisper of a dying man." At Wroughton it is again amplified and sent 70 miles to London, where the London

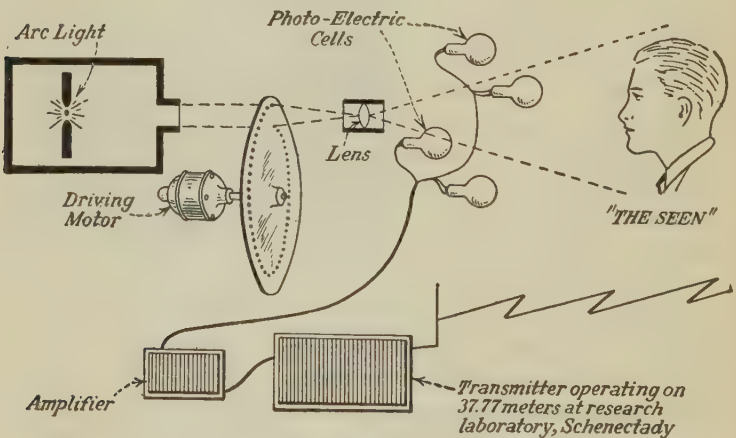
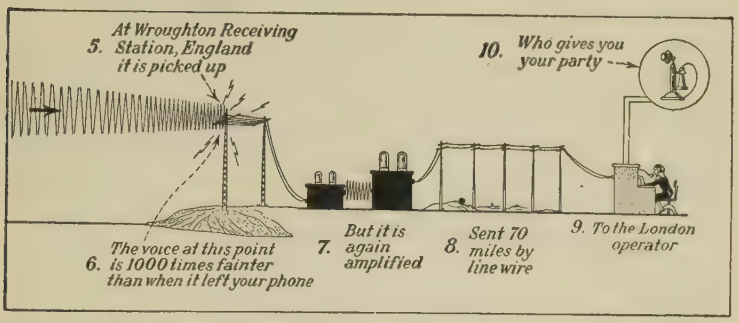


FIG. 733. — Diagram to show television.

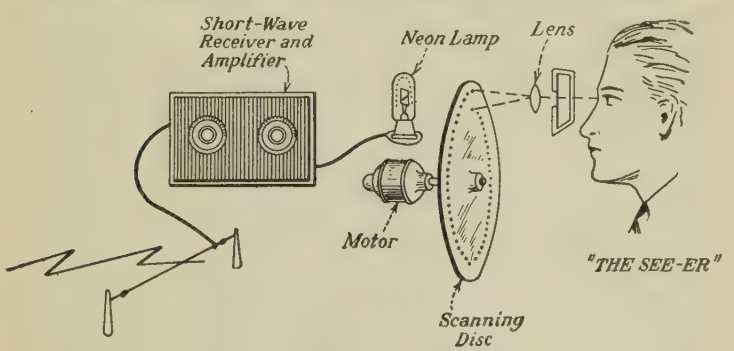
operator connects you with your party. Fig. 732 shows the different stages used in trans-Atlantic telephony. Your

reply from London comes back by wire to Rugby, England, where it is amplified as before, and sent to New York by way of Houlton, Maine.


5. At Wroughton Receiving Station, England it is picked up
10. Who gives you your party
6. The voice at this point is 1000 times fainter than when it left your phone
7. But it is again amplified
8. Sent 70 miles by line wire
9. To the London operator

(*Courtesy of The Literary Digest.*)

603. Television. For *television*, which comes from the Greek word meaning "distant" and the Latin word meaning "seeing," a transmitting and a receiving apparatus are needed just as in the case of radio. Two new pieces of apparatus are necessary, the *photo-electric cell*, which has been called "an electrical eye," and the *neon*



(*Courtesy of Current Science.*)

lamp, which glows *instantly* when the current is on and goes out *instantly* when the current is turned off. Its

brilliancy also varies with any variation in the amount of current it receives.

At the transmitting station, a powerful arc light is used to illuminate the object or person to "be seen." The light waves pass through the holes in a disc which is driven by an electric motor. (See Fig. 733.) As the disc makes about 18 revolutions per second, spots of light strike the face, one at a time, until the entire area has been covered. These spots of light are reflected from the face to one or more photo-electric cells. This cell is a vacuum tube. Part of its inside surface is coated with a metal such as potassium or cæsium, which is *sensitive* to light. The negative lead-in wire is connected to this photo-electrically active metal and the positive wire is connected to a ring of inactive metal like nickel or platinum. The metal potassium emits electrons when light shines upon it, and the number of electrons emitted is directly proportional to the intensity of the light. Hence if we connect a photo-electric cell to a battery and galvanometer, as shown in Fig. 734, the current flowing through the galvanometer will fluctuate as the intensity of light that is focused upon the cell varies. In a like manner, the spots of light which are reflected from the face, varying in intensity as they do, will cause the photo-electric cell to produce corresponding fluctuations in the current flowing from it. Such a current can be amplified and transmitted in the same manner as radio waves.

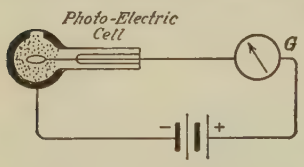


Fig. 734.— Photo-electric cell.

At the receiving station the waves are again amplified and impressed upon a neon lamp. Here the brightness of this lamp will vary instantly just exactly the same as the current in the photo-electric cell varied. A duplicate disc at the receiving station is turned by another motor at exactly the same speed (synchronism) as the disc at the transmitting

station. The rays from the neon lamp pass through the holes in the disc and can be viewed by a person at the receiving station. These flashes of light will have the same relative brightness as the light spots reflected to the photo-electric cells. In our study of the persistence of vision, we learned that an image does not fade from the retina in less than $\frac{1}{16}$ of a second. Just as this phenomenon enables the retina of the eye to form a composite picture of some 20 or more pictures flashed upon a screen, so the eye scans the area mapped by these spots of light and blends them into a composite picture of the person at the transmitting station.

B. CATHODE RAYS

604. Electrical Discharge in Partial Vacua. We have learned that a pressure of 27,000 volts is necessary to produce a spark 1 cm. long across an air-gap; if the terminals of the secondary of an induction coil are pointed, a pressure of only about 8000 volts is needed to produce a spark of that length. Suppose we have a tube two or three feet long with metal terminals sealed in each end. If we connect it to the secondary of an induction coil as in Fig. 735, the spark takes the short path AB as the discharge occurs. If we pump out some of the air from the glass tube, the discharge then occurs between the terminals $A'B'$, and the whole tube becomes filled with a bluish-violet light. This experiment shows that the resistance offered by a partial vacuum is decidedly less than that of a very much shorter air-gap.

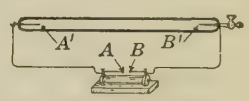


FIG. 735. — Partial vacuum tube.

FIG. 736.— Geissler tube.

The color of the light may be varied by filling the tube with rarefied gases, such as hydrogen, nitrogen, chlorine, etc. Very beautiful effects may be pro-

duced in a darkened room by using different gases in varicolored glass tubes. Such tubes are known as Geissler tubes. (See Fig. 736.)

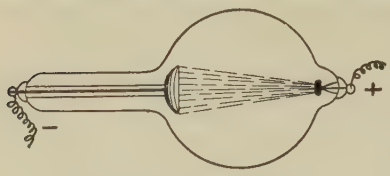


FIG. 737. — Cathode tube

Tubes of this nature filled with *neon* gas are used for testing spark plugs. When one end of the tube is held against the plug, a crimson light may be observed, if the spark-plug is firing properly.

Many advertising signs also utilize rarefied gases to conduct the current between electrodes sealed in the ends of the tubes.

605. Cathode Rays. When a glass tube of the form shown in Fig. 737 is attached to the terminals of an induction coil and the atmospheric pressure in the tube is reduced to less than 0.001 mm. of mercury, an invisible radiation called the cathode rays is given off from the cathode at nearly right angles.

FIG. 738.— Heat effects of cathode rays.

The presence of these *cathode rays* may be detected: (1) by their heating effects; (2) by their fluorescent effects; and (3) by the shadows they produce.

FIG. 739. — Zinc sulphide fluoresces.

(1) If a piece of tungsten is sealed in the tube of Fig. 738 so that these rays may be concentrated upon it, the bombardment of the rays heats the tungsten white hot in a short time.

(2) As the cathode rays fall upon the glass tube a yellowish green fluorescence is produced. Pieces of zinc sulphide or of colored glass also fluoresce readily when exposed to the cathode rays in an apparatus like that shown in Fig. 739.

(3) If a piece of metal is interposed in the path of the rays as in Fig. 740 a shadow is produced. The glass fluoresces on all sides, but directly back of the metal it is dark; this shows that the cathode rays have been intercepted by the metal plate.

606. Nature of the Cathode Rays. A piece of metal containing a narrow slit may be placed in the path of the cathode rays so that a single stream of rays passes through the slit as shown in Fig. 741. If a magnet is held near the tube, the cathode rays are deflected, such deflection becoming visible by the fluorescence of a screen placed in the tube. As a result of this and other experiments it has been found that the *cathode rays are negatively charged particles given off from the cathode.* J. J. Thomson calls these particles *electrons.* Their mass has been determined; it is about $\frac{1}{1840}$ as great as the mass of the hydrogen atom, which is the lightest atom known. The speed of the cathode particles varies from 20,000 miles to over 100,000 miles per second.

FIG. 740. — Shadow effect of cathode rays.

607. The Coolidge Tube. The cathode rays have been known since 1875, when they were discovered by Sir William Crookes. About 1926, our newspapers contained accounts of the remarkable things that the cathode rays do when they impinge upon different kinds of matter *outside* of the tube. Dr. W. D. Coolidge had constructed a tube, one end of which contained a thin nickel disc through which the cathode rays could pass. By using a voltage of 350,000, he was able to produce as many cathode, or beta, rays as 1,000,000 grams of radium bromide can produce. The air in front of the

FIG. 741. — Effect of magnet on cathode rays.

metal disc assumes a purplish glow as its molecules are ionized by these high-speed particles. Germs and spores are destroyed by these cathode rays. Calcite and granite fluoresce, and acetylene gas is changed into a solid powder. Their effect does not extend more than about two feet beyond the metal disc. Thus far no practical use has been found for such cathode rays.

C. X-RAYS

608. X-rays. The X-ray bulb differs little from the Crookes tube, which is used to produce cathode rays. If a tungsten or platinum disc is placed in a cathode bulb in such position that the cathode rays are concentrated upon it, a different type of invisible radiation is produced, Fig. 742. These radiations are called *X-rays;* or they are sometimes called from their discoverer, the Roentgen rays. The X-rays differ from the cathode rays, since they are not affected by a magnet. Unlike light rays, they cannot be reflected or refracted; hence they cannot be focused. It is quite certain that the X-rays consist of very short waves set up in the ether by the bombardment of the cathode particles upon the metal disc.

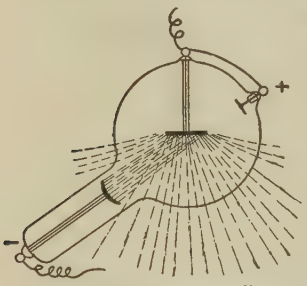


Fig. 742. — X-ray bulb.

609. Uses of X-rays. The most important use of X-rays depends upon their ability: (1) to affect a photographic plate; (2) to penetrate various kinds of matter which is opaque to light, such as wood, flesh, leather, etc. Their penetrating power depends upon the degree to which the bulb producing them is exhausted, and upon the voltage used. The rays from a very high vacuum bulb are very penetrating; they are called "hard rays." The less penetrating rays produced by a bulb with lower exhaustion are

called "soft rays." The X-rays do not penetrate bones and metals as readily as they do wood and fleshy tissues.

These properties of X-rays make them very useful to surgeons in studying the fractures of bones and in locating foreign substances in the body. X-ray photographs are taken by placing the object on the cover of the holder in which the plate is enclosed and then bringing the X-ray tube a few inches from it. Such photographs are called *radiographs* or *skiagraphs*. Since the rays are not focused, the picture is

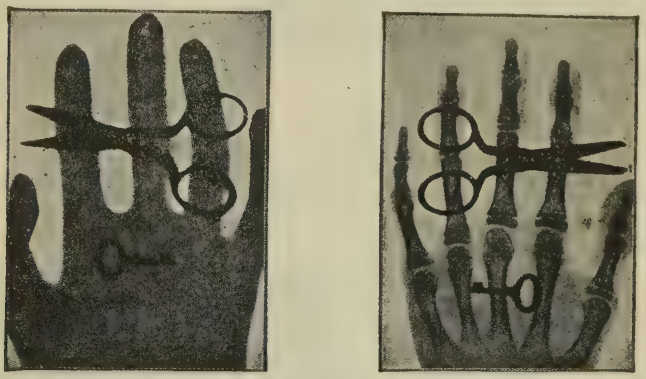


FIG. 743. — Radiographs. The cut at the left was made by the action of radium rays. The one at the right by the X-rays. (*Courtesy of Radium Limited, U. S. A.*)

only a shadow picture. The bones and metallic objects are darker, because they absorb the X-rays more readily. (See Fig. 743.) Before radiographs of the stomach and intestinal tract are taken, the patient is given large doses of buttermilk containing barium sulphate and bismuth subnitrate in suspension. These heavy solids cause the outline shadows of these organs to become very distinct. Cancer on the walls of the stomach shows so clearly that 90% of the diagnoses following X-ray examination prove correct.

The X-ray is used by a large shoe company to test shoes to see if the nailing is properly done. Department stores

sometimes use the X-ray to aid in fitting shoes, but they do not use it with cheap shoes. Pearls are nearly transparent to the X-rays, but imitation pearls are decidedly dark by contrast. The X-ray has also been used with considerable success in determining whether paintings are the work of the old masters or mere copies. The X-ray is now being used in the study of the structure of crystals.

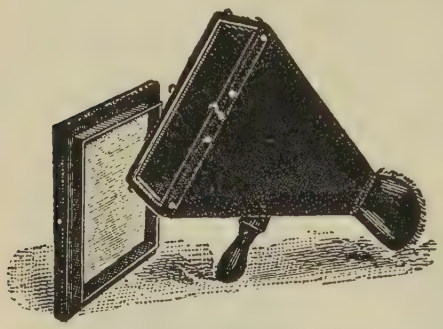


Fig. 744. — Fluoroscope.

610. The Fluoroscope. Thomas A. Edison devised a hood and screen, called a *fluoroscope,* which may be used to show the effects of the X-rays without photographing them. The sides of the box, Fig. 744, are opaque. The screen is coated with platinum-barium-cyanide, a chemical which Edison found to be exceedingly sensitive to the fluorescent effects of the X-rays. If one holds his hand between a fluoroscope screen and an X-ray tube, the bones of the hand may be clearly distinguished. By its use a doctor can peer into a living body and examine

Fig. 745.— Contour of abdominal organs as seen on screen.

the vital organs. (See Fig. 745.) One woman, for example, was examined for tumor of the stomach. The fluoroscope showed that the obstruction was not on the *walls* of the stomach, but within the stomach itself. Later a large ball of hair was removed from the woman's stomach.

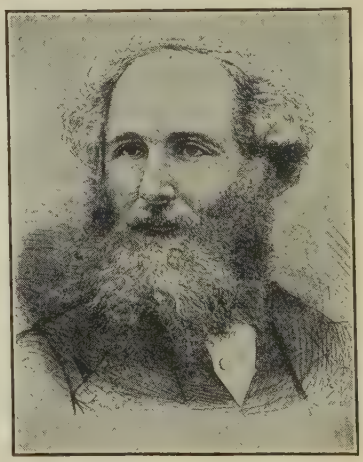
D. RADIO-ACTIVITY

611. Radio-activity. In 1896 Henri Becquerel, a Frenchman, performed an epoch-making experiment. He found that a piece of metallic uranium darkens a photographic plate, even when the plate is wrapped in a piece of opaque paper and kept in the dark. Hence he concluded that uranium gives off *radiations* similar to the X-rays. Such radiations pass through substances opaque to ordinary light, but they are stopped by bones, metal, etc. Substances that give off radiations of this nature are said to be radio-active.

612. Discovery of Radium. Soon after this discovery by Becquerel, M. and Mme. Curie began a series of experiments to determine whether other elements show radio-activity. Of the elements known at that time, thorium, an element used in making Welsbach gas mantles, was the only one that exhibited this property. Mme. Curie did find, however, that pitchblende, the mineral from which uranium is extracted, is four times as active as the pure uranium. Therefore she concluded that pitchblende must contain some other element more active than uranium itself. She patiently worked over several tons of pitchblende and succeeded in isolating a few milligrams of the chloride of an element that is more than 1,000,000 times as active as uranium. She named the element *radium*. Radium is usually used in the form of its salts; the chloride, bromide, or carbonate for example. Mme. Curie succeeded, several years later, in 1910, in isolating metallic radium. Both the metal and its salts give off the *Becquerel rays*.

Marie Sklodowska Curie (1867–) was born in Poland. After Henri Becquerel discovered the radio-activity of uranium, Mme. Curie in collaboration with her husband, Pierre Curie, examined other substances to learn whether they are radio-active. From pitchblende she isolated radium. She also discovered polonium. In 1903 M. and Mme. Curie shared the Nobel prize with Becquerel. The College women of America presented Mme. Curie with one gram of radium to be used for research work.

James Clerk-Maxwell (1831–1879) was a Scotch physicist. In 1873 he published a treatise on "Electricity and Magnetism." He believed that electro-magnetic energy travels through space in the same manner as light and at the same velocity. His electro-magnetic theory has been confirmed by experiment, and by the discovery of the Hertzian waves. Maxwell investigated the nature of color and the kinetic theory of matter.



In 1921, Madame Curie, who is now professor of physics at the University of Paris, visited the United States of America. The sum of $120,000 had been raised by subscription among the women of the United States for the purchase of one gram of radium bromide. This gift of the American women was presented to Madame Curie by the President of the United States.

613. Radium. In many respects radium is the most interesting element ever discovered. Its properties are unusual and it *does* things. 1. It *affects a photographic plate,* even through opaque substances like paper, wood, and *thin* sheets of metal. (See Fig. 743.) 2. Radium and its compounds *discharge an electroscope;* they knock to pieces the surrounding air molecules, breaking them up into ions and thus making them conductors. The activity of a sample of radium bromide may be determined by the rate at which it will discharge an electroscope of the type shown in Fig. 547. The electroscope is many times as sensitive for determining the value of radium salts as a chemical balance, even one weighing to 0.00001 gm.

Fig. 746. — Hands of a watch photographed by their radium coating.

3. Radium salts produce *fluorescence* with certain salts, just as the X-rays do. Hence a mixture of a very small quantity of radium bromide and zinc sulphide is luminous in the dark. Such a mixture is used as a luminous paint for coating the dials of airplane instruments, the hands and dials of watches, and the sights of guns that are used for night firing. (See Fig. 746.) 4. Radium is *active chemically;* it decomposes water, changes oxygen to ozone, imparts a purple color to glass, etc. 5. The *physiological effects* of radium are pronounced. It may destroy the germinating power of seeds, kill bacteria, or even destroy small animals. Radium produces frightful burns that require a long time to heal. Some early investi-

gators were severely burned by radium while experimenting with it. 6. The salts of radium *glow in the dark*, producing a pale phosphorescence. In the daylight they resemble common table salt in appearance. They do not give off light enough to be observed in ordinary daylight. 7. Radium *gives off enough heat* every hour to melt 1.5 times its

FIG. 747. — Separating radium bromide from barium salts by fractional crystallization.

weight of ice, or about 120 calories per gram. This heat is given off quite continuously, since radium loses only one half its energy in the first 1700 years, one half of what remains in the next 1700 years, and so on. 8. Radium is rare and expensive. From new ores discovered in the Belgian Congo, radium salts can be extracted more cheaply than from the pitchblende or carnotite ores; the present price is about $70,000 per gram. *Radium is always found in uranium ores.* In fact it is now known that *uranium is the parent of*

radium. But in radium ores, there is only about 1 part of radium to a little more than 3,000,000 parts of uranium. To produce 1 gram of radium about 500 tons of the ore must be used. Fig. 747 shows the large evaporating dishes used to carry out the 75 successive crystallizations needed to separate radium salts from those of barium.

614. Nature of the Becquerel Rays. The Becquerel rays that are emitted by such elements as uranium, thorium, and radium have been very carefully studied. In 1899 Ernest Rutherford, then of McGill University, discovered that the Becquerel rays are complex, consisting of three different classes:

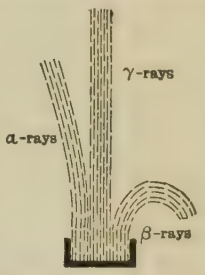


FIG. 748. — Effect of magnet on rays.

(1) The α-rays, or *alpha rays*, are identical with *positively* charged helium atoms. Their mass is nearly four times that of the hydrogen atom; their velocity is from 10,000 to 20,000 miles per second. The alpha rays do not have as great penetrating power as the other rays; a very thin piece of aluminum foil or a thin sheet of paper is sufficient to intercept them. On the other hand, they are very efficient in ionizing air molecules; hence they discharge an electroscope rapidly. Severe radium burns are largely due to the alpha rays.

(2) The β-rays, or *beta rays*, are identical with the cathode rays. They consist of negatively charged particles of matter, or electrons. They are only about $\frac{1}{1840}$ as heavy as the hydrogen atom. Since they travel at a velocity of from 60,000 miles per second to 160,000 miles per second, they have much greater penetrating power than the alpha particles. The β-ray seems to be identical with the charge carried by the negative ion in solution, or during electrolysis.

(3) The γ-rays, or *gamma rays*, appear to be of the same nature as the X-rays. They are more penetrating than either the alpha or the beta rays. The gamma rays are

believed to be caused by the impact of beta particles upon surrounding matter. Fig. 748 shows the effect of a powerful magnetic field on the complex Becquerel rays emitted from a small amount of radium. The heavy alpha particles are deflected slightly in one direction; the lighter beta particles are deflected more markedly in the other direction; the gamma rays are not deflected at all. By the use of such a magnetic field, Rutherford learned the nature of the Becquerel rays.

615. The Spinthariscope. In 1903, Sir Wm. Crookes devised a little instrument called the *spinthariscope;* by the use of this instrument it may be shown that particles are being continually emitted from radium. A speck of radium is mounted over a zinc sulphide screen. As the particles emitted by the radium strike the screen, they produce fluorescence. When the screen is examined in the dark by the use of a lens, a succession of sparks is seen. Each flash is produced by the impact of an alpha particle on the screen.

616. Disintegration of the Atom. Because heat and light appear to be given off continuously from radio-active substances without any apparent loss of weight, it was at first believed that radium is an exception to the law of the conservation of matter and energy. More careful investigations show that radium does slowly lose its energy, one half in the first 1700 years.

The question naturally arises, "What is the source of all this energy?" A long series of experiments has furnished the answer to this question. *The atoms of radium and other radio-active elements are exploding or disintegrating.* The alpha and the beta rays are the products of atomic disintegration. *Spontaneously* certain heavy atoms are breaking down into simpler and lighter atoms. After an average life of 2500 years, for example, the radium atom explodes. The radium atom is 226 times as heavy as the hydrogen atom. When it explodes, it loses an alpha particle, which

becomes an atom of helium when it loses its charge of electricity. This helium atom weighs four times as much as the hydrogen atom. The remainder of the atom, 222 times the weight of the hydrogen atom, is a gas known as *radon*. Thus two gases, helium and radon, are formed when an atom of radium explodes. The beta particle is so light that its effect on the weight is slight.

Radon loses half its activity in a little less than 5 days. At Memorial Hospital in New York four grams of radium are kept in vaults. The radon which is produced by the disintegration of this radium is used for treating cancerous growths. *Radon* forms *radium A* when it disintegrates. As radium *A*, which is radio-active, breaks down, it forms successively the radio-active elements *radium B*, *radium C*, *D*, *E*, and *F*. Radium *F* loses an alpha-particle and forms an element that has an atomic weight of 206; it seems to be identical with lead. (See Fig. 749.) Thus while uranium is the parent of radium, its descendant is lead. Chemists scoffed at the idea of the old alchemists that one element could be transmuted into an-

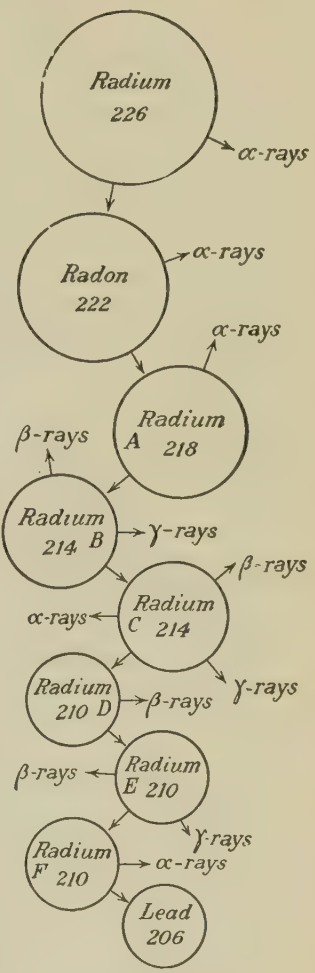


FIG. 749. — Disintegration of radium atom.

other; now they learn that *spontaneous transmutation* is going on constantly with certain elements.

617. Can Atomic Energy Be Utilized? We have learned that one gram of good coal in burning yields about 8000 calories. It is possible to compute the amount of heat liberated by one gram of radium when disintegrating, since we know that one gram yields about 120 calories of heat per hour throughout an average life of about 2500 years. The total amount is more than 300,000 times as much heat as can be obtained by burning an equal weight of coal.

J. J. Thomson has estimated that the energy stored in one gram of *hydrogen* equals 6×10^{11} foot pounds. Thus the energy in one gram ($\frac{1}{454}$ lb.) of hydrogen would be sufficient to lift 10 of our largest battleships (32,000 tons each) higher than the top of Mt. Blanc, over $3\frac{1}{2}$ miles. Whether man will ever learn how to unlock this tremendous storehouse of energy and put it to practical use is problematical. There is no known chemical or physical agency that either accelerates or retards the disintegration of atoms.

It is reported that Rutherford succeeded in disintegrating the nitrogen atom by bombarding it with particles given off from radio-active substances. This appears to be a step toward solving this interesting problem, but we must keep in mind the fact that Rutherford used as much energy to knock the nitrogen atoms to pieces as he obtained by their disintegration. Therefore the biggest part of the problem remains to be solved. Possibly at some future time atomic energy may be used to replace coal and gasoline for fuel and power purposes. It is possible that future generations may learn how to transmute lead and other base metals into more precious ones. No one can foretell what the future may bring, especially when we consider the rapid strides that physics and chemistry have made during the last few decades.

CHAPTER 29

THE AUTOMOBILE

A. THE AUTOMOBILE

Vocabulary

Carburetor, a device used to vaporize gasoline and mix it with air so that an explosive mixture will be formed.

Clutch, a device to connect the engine shaft with the drive shaft.

Transmission gears, sets of gear-wheels used to vary the speed of a car, and to reverse the car.

Differential, a device used in the divided rear axle to permit one rear wheel to turn faster than the other.

Distributor, a device used to distribute the spark to the cylinders in the proper order and at the right time.

618. Introductory. Although there are over 22,000,000 automobiles in the United States, one for every five inhabitants, yet the great majority of those driving cars have very little knowledge of the car's mechanism. Since such knowledge helps to increase the comfort and the safety of the driver and his passengers, no text-book in physics can be quite complete if a study of the automobile is neglected. Nearly all the fundamental principles of this science are used in the construction and operation of a modern automobile. Its study may form an excellent review of the subject matter that we have already studied.

For convenience, the automobile may be considered as consisting of three parts: (1). the power plant; (2). the chassis, or running gears (see Fig. 750); and, (3). the body. The last named needs no discussion here. In this chapter, certain topics which have not been discussed will be taken up first; then other parts will be reviewed to show how they apply to this compound machine.

619. The Power Plant. 1. *Electric.* For some cars the motive power is electricity. A storage battery supplies the current. The armature of an electric motor is attached to the rear axle, as shown in Fig. 751. The electrically driven car has certain advantages. There is no need for a clutch or gear-shift. There is no motor to be warmed up in cold weather and no loss of energy from an idling motor. For these reasons many light delivery trucks are equipped with

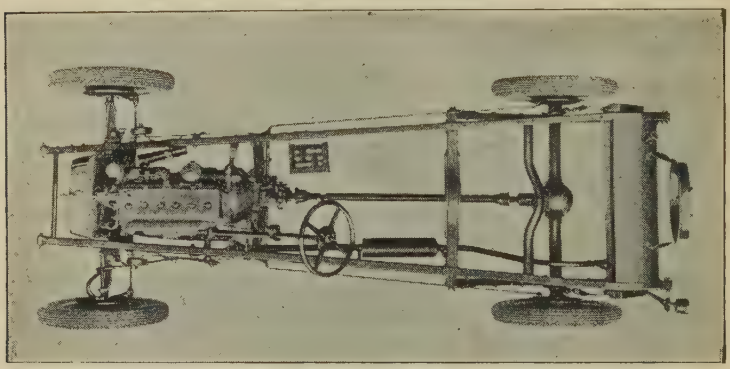


FIG. 750. — Chassis, showing frame, battery, engine, transmission, differential, muffler, etc.

electric drive. The storage batteries are then charged at night to be ready for the next day's work. On the other hand, electric power is not suitable for touring. The storage batteries needed for a run of even 200 miles would add too much to the weight of the car. Several hours would be needed to recharge the batteries.

2. *Steam.* Some cars have been manufactured in which the steam engine is used to furnish the motive power. Kerosene or some oil is burned to supply the steam. Although no clutch is needed and the speed may be varied without gears, the cost and weight of the steam-driven car have prevented its extensive use.

3. *Gas.* It was in 1860 that Lenoir, a Frenchman, made

the first practical gas engine. It was very wasteful of gas because the gas was not compressed before ignition. Eighteen years later Otto, a German, introduced the compression stroke, which cuts the gas consumption to about one third that of Lenoir's engine. These inventions have made pos-

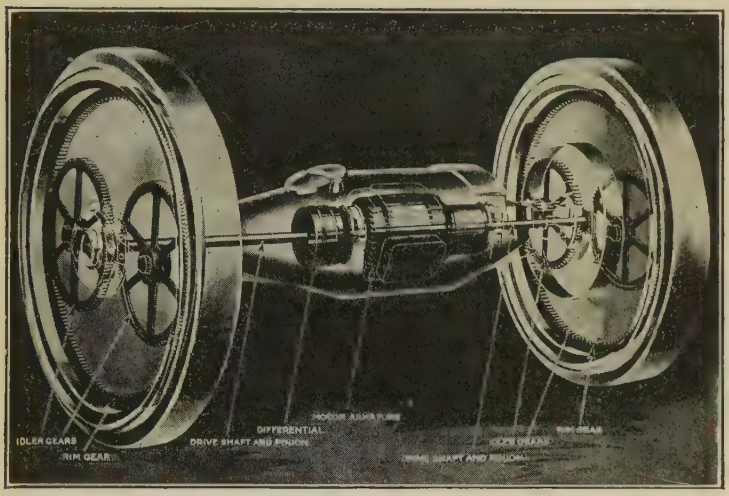


FIG. 751. — Axle driven by electric motor.

sible both the automobile and the airplane, because the gas engine may be light, and yet very powerful. (See Fig. 372.)

We have already studied the action of a single cylinder gas engine, § 312, and know some of its defects. Its speed cannot be varied through a wide range. It is apt to stop or stall when it runs slowly. Hence it will not start under load, unless transmission gears are used. The gas engine cannot be reversed. For these reasons a clutch and a set of transmission gears must be used with a gas-driven automobile.

The single-cylinder gasoline engine has only one power stroke in two complete revolutions, or one stroke for 720°

of rotation. Greater flexibility is secured by the addition of more cylinders, so timed that the power strokes follow one another successively. The early Cadillac car had only a single cylinder, and a 300-lb. flywheel was required to keep the car moving between successive strokes. Now the number

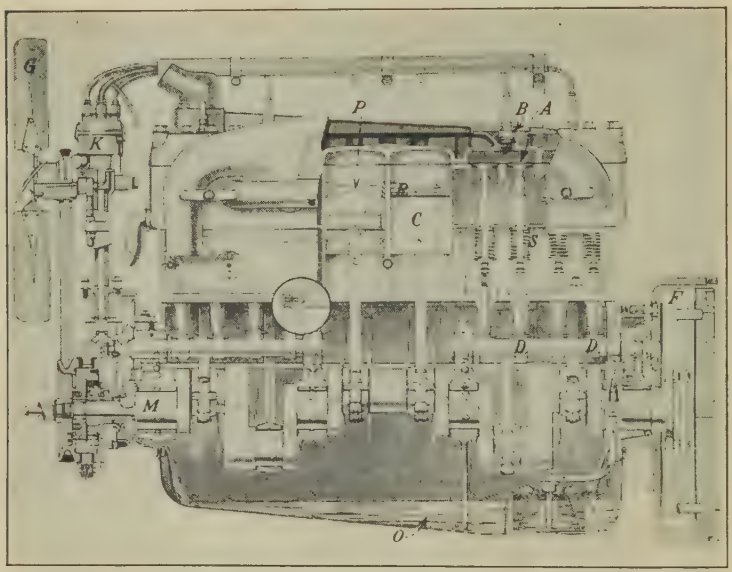


FIG. 752. — Six-cylinder engine. *A*. Poppet valve. *B*. Spark plug. *C*. Piston. *D*. Cam shaft. *F*. Flywheel. *G*. Fan. *K*. Distributor. *M*. Crank-shaft bearing. *O*. Oil reservoir. *P*. Piston, sectional. *R*. Piston rings. *S*. Spring that controls valve.

of cylinders has grown to 2, 4, 6, and even 8, all acting on the same crank-shaft. Increasing the number of cylinders does not necessarily make the engine more powerful, but a six-cylinder engine may be throttled down in traffic with less danger of stalling than a four-cylinder engine.

The sectional diagram of Fig. 752 shows a modern six-cylinder engine. The water jacket and the cylinder walls of the middle cylinders are cut away to show the construc-

tion. Four piston rings, three at the top and one near the bottom of the piston, are used to make the piston fit the cylinder tightly. The fifth cylinder shows the poppet valves, and how they are controlled by the cam shaft. As the cams push up against the valve stems, the valve is opened. The spring closes the valve at the proper time. The position of the spark plug can be seen in the head of this cylinder. At the left, between the fan and the cylinder block, is the distributor, which is so timed that it will produce an electric spark in each cylinder in the proper firing order. The arrows show how oil is forced from the oil reservoir along the crank-shaft to secure proper lubrication.

620. The Carburetor. Contrary to popular belief, liquid gasoline does not explode. Its vapor will explode, if it is mixed with the right proportion of air. The carburetor is designed to vaporize gasoline and to mix it with the right amount of air before it enters the cylinders of the engine through the intake manifold. If the cylinders are *flooded* with gasoline vapor which is unmixed with air, no explosion can occur, and the engine will not start.

The operation of the carburetor may be better understood, if we refer to Fig. 753. As the gasoline from the vacuum tank enters the carburetor at A, it gradually lifts the float F until the levers L and L' close the valve at V. Thus the gasoline in the float chamber is kept at about the same level as the nozzle N. The gasoline is vaporized as it flows through the spray nozzle N into the mixing chamber, where it is thoroughly mixed with air coming in through B. When the throttle T is opened, an explosive mixture is

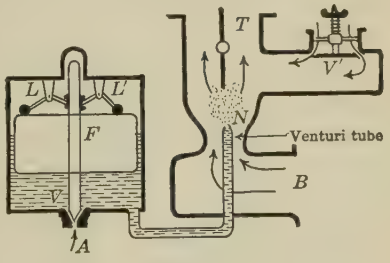


FIG. 753. — Diagram of carburetor.

pushed into the engine. The *venturi* tube is narrowed at N to give the air a higher velocity in this part of the tube. Such increased velocity causes the gasoline to evaporate more rapidly.

If an *ideal* carburetor could be constructed, it would vaporize the gasoline perfectly and mix it with just enough air to burn *completely* every molecule. Such a condition is impossible for three reasons: 1. Gasoline is not a compound, but a mixture of compounds that have different boiling points. One sample of gasoline needs 47 parts of air to one of vapor for complete combustion, but another sample may require 60 parts of air to one of vapor. 2. Perfect vaporization is not secured until the engine warms up, and a mixture richer in gasoline must be used when starting. This is secured to some extent by the use of the "choke" which cuts off some of the air supply. 3. A carburetor that is adjusted for one speed is not perfectly adjusted at other speeds. When the engine is running rapidly, the increased suction makes the evaporation of the gasoline so rapid that more air must be introduced to make a "leaner" mixture. This is accomplished by the use of the auxiliary air valve V'.

621. The Clutch. Since the working strokes of a gas engine are periodic, it will not start under load. Therefore a *clutch* must be used to connect the engine or *driving* machine with the *driven* parts. One member of the clutch is attached to the crank-shaft of the engine just back of the flywheel, or in combination with it; the other member is attached to the transmission shaft. When the engine is idling, one part of the clutch always rotates with it. This rotating part must be engaged with the member connected with the drive-shaft so gently that jerking is avoided, and so firmly that they turn together when engaged. For these reasons the friction material on the faces of the two members must slip a little as the car comes up to speed, and then hold firmly.

Several types of clutch are in use. Fig. 754 shows the *cone* clutch. Although this clutch is now little used, it is easier to understand. The flywheel F is hollowed out to receive the conical surface of the driven member M. As the operator pushes the foot lever L forward to *disengage* the clutch, the two members are separated and the flywheel revolves independently while the motor idles. As the operator lifts his foot slowly to *let in the clutch*, a spring pushes M forward until it is in contact with the rotating flywheel. The surface of M is covered with some friction material which slips some when pressure is first applied, and then holds firmly when the clutch is fully engaged. The *single plate dry disc clutch* is now much used on modern automobiles. Sometimes the *multiple disc clutch* of the type shown in Fig. 755 is used. There are two sets of discs, one attached to the crank-shaft and the other to the transmission shaft. One set of discs is covered with friction material.

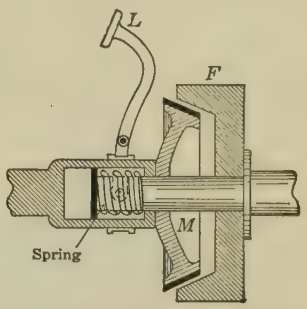


FIG. 754. — Cone clutch diagram.

622. The Transmission Gears. The driver of an automobile may vary his speed by regulating with the throttle or accelerator the amount of gas. Such control is satisfactory for driving on a level road. But to overcome the inertia of a heavy car at starting, or to drive the car up a steep hill, transmission gears are necessary to vary the speed of the car while the engine is still running at a rather high speed. The gas engine is not efficient at low speed. The majority of cars have three speeds forward and one speed in reverse.

The transmission system consists of three shafts. Two of them, a pinion shaft P connected with the engine through the clutch, and the main drive shaft D, Fig. 756, are on the

same direct line, but they may turn independently of each other. The third shaft, *C*, which operates parallel to the other two, is called the *countershaft*. The countershaft has

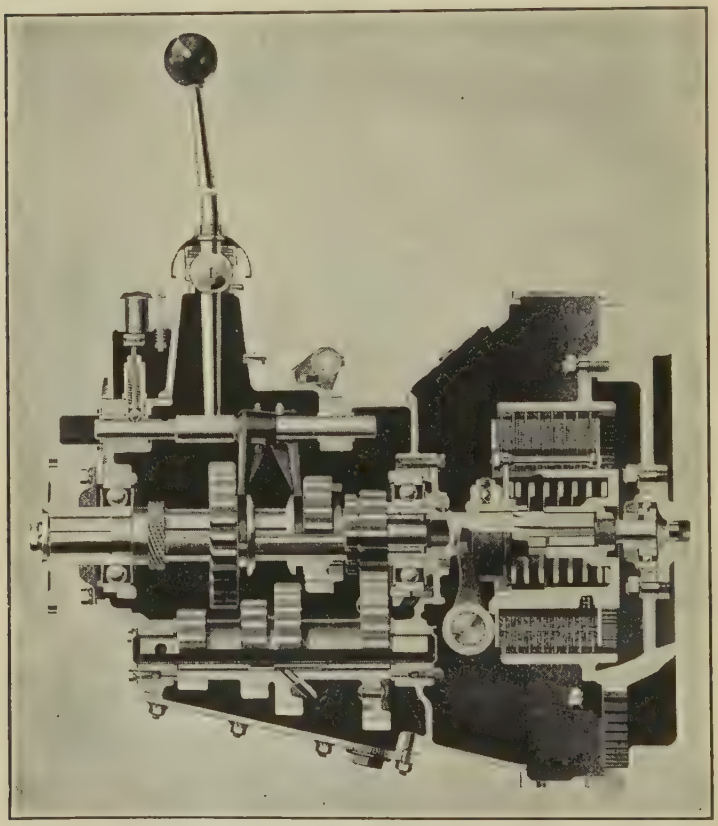


Fig. 755. — Multiple disc clutch and transmission gears. Note the use of ball bearings and roller bearings to reduce friction. The clutch and transmission are carefully housed to keep the parts free from dirt.

four gears, all fixed on the shaft so they turn with it. The gear *A* on the pinion shaft is always in mesh with the gear *B* on the countershaft. In § 204 we learned how two gear

wheels in mesh may be used to *vary speed.* For example, if the engine is making 2000 revolutions per minute, and the pinion gear *B* has twice as many teeth as *A*, then the countershaft will make only 1000 revolutions per minute. Every other gear wheel on the countershaft will make the same number of R.P.M. The *main drive shaft* has two gears, *F* and *E*, which may be slid forward or backward along the shaft; but *they always turn with it.* As they are slid backward or forward, they may mesh with the gears on the countershaft.

Neutral. In Fig. 756 *A* the gears are in neutral position. The pinion shaft and the countershaft both turn, in opposite directions, but they are not connected with the main drive shaft. This is the condition

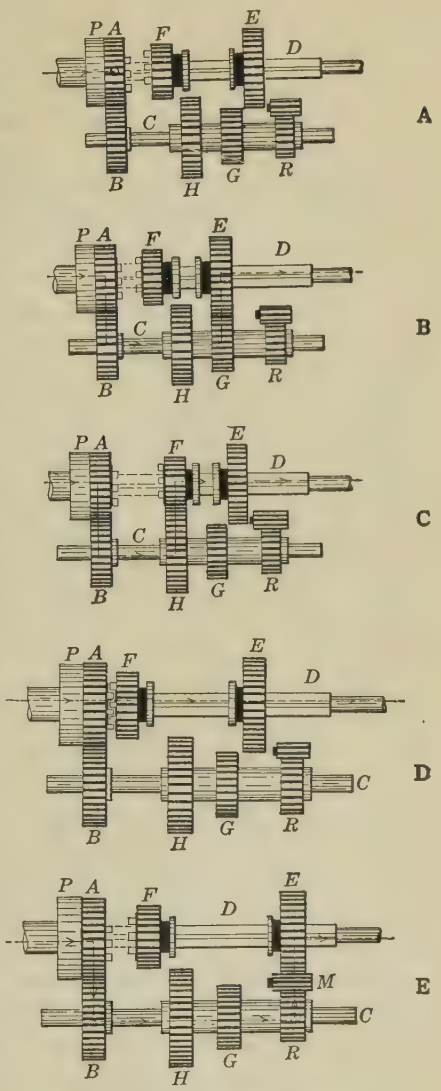


FIG. 756. — Transmission gears.

when the gear-shift lever is in the position shown in Fig. 755.

First or low speed. When the operator pulls the gear-shift lever back to the position marked 1 in Fig. 757, he moves the gear E of Fig. 756B forward along the drive shaft until it is in mesh with the small gear G on the countershaft. Suppose that E has twice as many teeth as G, then the drive shaft will make only one half as many revolutions per minute as the countershaft. The drive shaft will make only one fourth as many revolutions as the engine. The car is in low speed, and the power is transmitted as shown by the dotted line of Fig. 756B.

Second or intermediate speed. As the lever is shoved forward and to the right to the position marked 2, the gears E and F are pushed backward until E is out of mesh and F is in mesh with the gear H on the countershaft. The dotted line of Fig. 756C shows how the power is transmitted from the engine to the drive-shaft. If F and H have the same number of teeth, then the countershaft and the drive-shaft will have the same number of R.P.M., both of them just half that of the crank-shaft of the engine.

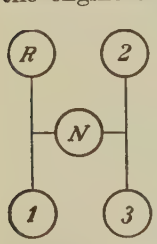


Fig. 757. — H-diagram to show gear-shift.

Third or high speed. When the gear lever is pulled back to position 3 in Fig. 757, then the gear F is slid forward until it is locked by means of teeth to the pinion shaft, and the drive is *direct* from the crank-shaft of the engine. The drive shaft or the propeller shaft is now making the same number of R.P.M. as the engine. (See Fig. 756D.) The countershaft is now idling.

Reverse. When the operator pushes the gear-shift lever forward and to the left to position R, the sliding gear E of Fig. 756E, is in mesh with a small idler gear M. Three gears are now in mesh as shown in Fig. 758. The pupil will note that the drive-shaft is now turning in the opposite

direction to that of the crank-shaft. Thus the engine continues to turn in the same direction, but the drive-shaft is reversed. (See Fig. 756*E*.) The student should compare these diagrams with the transmission gear-set of Fig. 755.

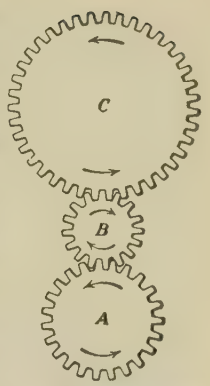


Fig. 758. — Wheels *A* and *B* turn in opposite directions.

623. The Differential. The transmission system is connected with the *differential* on the rear axle by means of two universal joints and the drive-shaft. (See Fig. 768.) In rounding a corner, the outer wheel of a car must travel faster than the inside wheel. Since the driving power of the engine is transmitted to the rear axle, a device must be used so that the two rear wheels will both drive together; and it must permit one wheel to travel faster than the other on curves. The *differential*, which is placed between the two parts of the divided rear axle, accomplishes both of these purposes. (See Fig. 759.) The driving pinion, *A*, which is attached to the drive-shaft, rotates the bevel gear *B*, which is rigidly attached to the frame *F*, and through the frame to the gears *C* and *E*. These parts must all rotate as a unit within the differential housing. On a straight road, the gears *C* and *E* do not rotate on their axes, but they are carried around with the frame *F*. As they revolve with the frame, they turn the gears *D* and *G* at the same speed. These gears are attached to the inner ends of the divided rear axle.

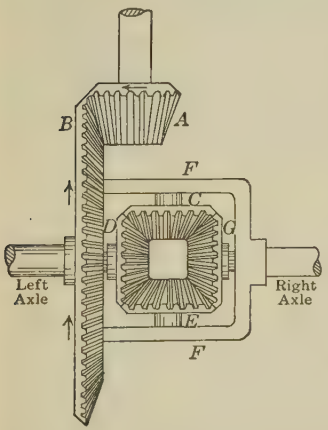


Fig. 759. — Differential diagram.

As they turn the axles, the rear wheels, which are rigidly attached to the other ends of these axles, drive the car. When the right axle turns faster than the left on a curve, then the gears C and E turn on their axes in opposite directions to compensate for the difference in speed of the two rear wheels. If one wheel stops, the other may continue to turn. A non-skid chain on one rear wheel is of no value on slippery roads. While one wheel grips, the other spins around rapidly, but the car does not move. The spur-gear differential of Fig. 760 is used on some motor trucks so that *either* wheel will drive.

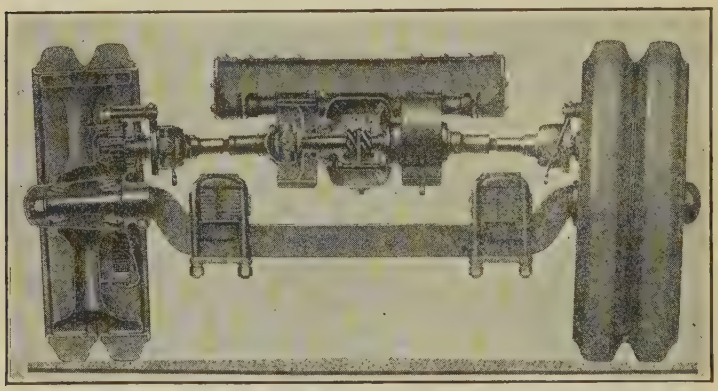


FIG. 760. — Spur-gear differential. With this type of differential either wheel will drive. Note the speed reduction gears between the false and the true axle.

We have already seen how the speed may be varied by means of transmission gears. There is a gear reduction in the differential. If the pinion gear has 15 teeth and the bevel gear has 65, then at high speed the engine will be making 65 revolutions while the rear wheels are making only 15. The *gear ratio* on such a differential is 4.33 to 1. Fig. 766 shows a sectional view of a rear axle with the housing cut away to show the differential.

624. The Ignition System. In the operation of a gas engine, the spark must occur at just the right time to ignite the explosive mixture. It must also occur in the proper cylinder. To accomplish this a *timer* and *distributor* must be used. A battery system is generally used with a spark coil to produce the spark needed for ignition. A storage battery, which is charged while the engine is running, supplies the necessary current.

In Fig. 761, *B* represents a six-volt battery. One terminal is connected to the metal frame and to the engine; the other

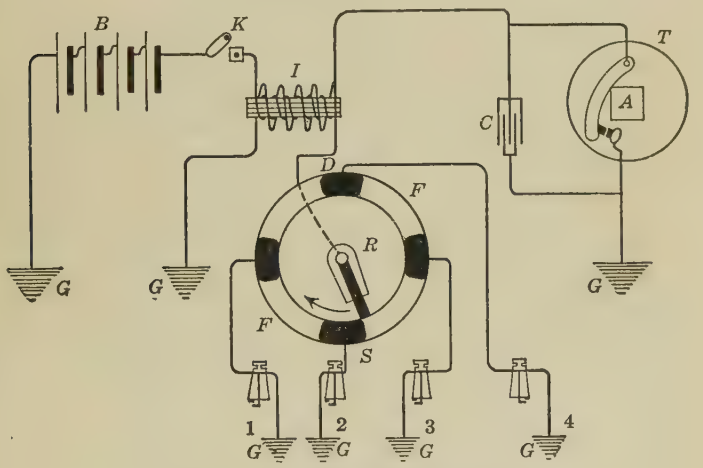


Fig. 761. — Simple ignition diagram.

terminal is connected by means of the switch *K*, with the primary of an induction coil. The timer *T* is used to "break" the circuit in the primary and thus induce a high voltage in the secondary coil *I*. One terminal of the secondary coil is grounded and the other terminal is connected to the rotor *R* of the distributor. As this rotor makes contact with the metal segment *S*, the induced voltage is high enough to cause a spark to leap across the gap be-

tween the two terminals of the spark plug in cylinder two.

The diagram shows how each of the four cylinders will fire in turn. As the cam *A* of the timer rotates, it will break the circuit four times during one revolution. A condenser is used at *C* to fatten the spark. The fiber ring *F* is made of insulating material, but each one of the metal segments is connected with a spark plug. As the rotor turns in the direction shown by the arrow, a spark will be produced in spark plugs numbered 2, 1, 4, and 3 in turn as it makes contact with the metal segments successively. Both the timer and distributor are geared with the engine so the timing will be perfect. Generally both are set on the same shaft. They are geared to rotate just half as fast as the crank-shaft, since an explosion occurs once in two revolutions.

The combustion of the gasoline mixture is not instantaneous. When the engine is running fast, the time required for the complete combustion may be so long comparatively that the gas is not completely burned before the power stroke is completed. Then some of the unburned gas will escape through the exhaust. This difficulty is met by *advancing the spark* a few degrees so that the explosion will occur a little before the piston starts its working stroke. In order to give a fraction of a second more time for the gas to burn, it is ignited by the advanced spark before the compression stroke is quite finished. The spark is advanced by a lever which shifts the fiber ring so that it is rotated a few degrees in a direction opposite to that of the moving rotor. Thus the segments on the ring make contact with the rotor more quickly. Moving the lever in the opposite direction *retards* the spark.

B. THE AUTOMOBILE AS A REVIEW

625. Introductory. If every student could take apart an automobile, study the workings of each part, and then re-

assemble the car, he would gain quite a complete knowledge of the science of physics. There are very few important principles or laws that are not utilized in the manufacture of automobiles. For these reasons it will be interesting to review from the standpoint of the automobile the various chapters we have studied in physics.

626. Review of Mechanics. *Chap. 1.* Much attention must be paid to the materials of which a car is constructed. In the testing laboratories men test different materials to determine their *hardness*, *brittleness*, *tenacity*, *malleability*, and *elasticity*. For example, chrome-vanadium steel is both *hard* and *tough*. Hence it finds use in making springs, transmission gears, axles, etc. Aluminum is used in the parts of some cars because its *density* is less than that of steel. The cylinders of some cars are machined to 0.001 in. Balls or rollers for bearings are assorted so closely that they do not vary more than 0.0002 in. Hence in the industry there is need for *accurate* and *precise measurements*.

On account of its *inertia*, a car is hard to start and hard to stop. The heavy flywheel keeps the engine running smoothly between successive power strokes. Too often motorists have demonstrated the *law of impenetrability* by proving that two objects cannot occupy the same place at the same time.

Chap. 2. A leak in the radiator demonstrates liquid *pressure*. When we inflate a tire, we note that the air pressure (fluid) is transmitted equally in all directions. *Pascal's Law* is also utilized in the hydraulic braking system and in the hydraulic hoist for lifting cars. A reversed application of this principle is utilized in the hydraulic shock absorber. (See Fig. 762.)

The float in the carburetor that controls the flow of gasoline is an application of *Archimedes' principle*, and a similar application of *flotation* or *buoyancy* is sometimes utilized in the gasoline gauge.

A special hydrometer, Fig. 607, is used to test the *specific weight* of the battery fluid. A fully charged battery should show a specific weight of about 1.300; if it is fully discharged, it may run as low as 1.15. The *freezmeter* is a modified form of hydrometer used to determine the freezing point of a mixture of water and denatured alcohol as used in automobile radiators. When the proportion of alcohol is decreased on account of its more rapid evaporation, the specific weight of the mixture that is left rises and it will also freeze more quickly.

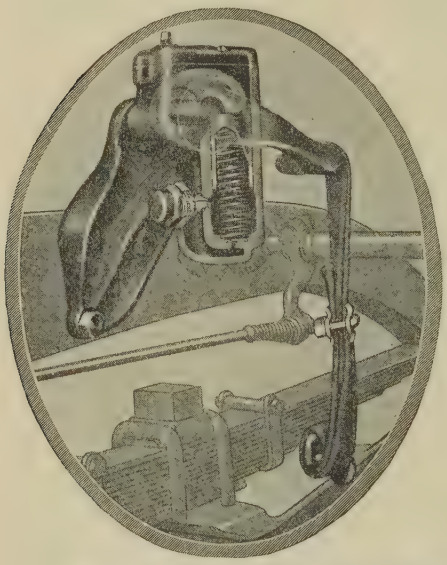


Fig. 762. — The piston of the hydraulic shock absorber forces oil slowly through restricted passages.

Chap. 3. Wind resistance affords ample proof that air exerts *pressure* and that it has *weight.* The fenders of modern cars are so curved that they will offer as little resistance as possible to air currents. The body of the car is also designed with stream lines for the same purpose. Racing cars, for example, are made with the rear pointed to prevent the formation of a partial vacuum behind a rapidly moving car. (See Fig. 763.) The air pressure on the surface of the gasoline in the tank pushes the gasoline up into the *vacuum tank.*

Fig. 763. — Partial vacuum retards motion of car.

The *compressibility* of gases as used in pumping up tires is an application of *Boyle's law*. A tire gauge is used to measure the magnitude of such pressure. When a blow-out occurs, the *expansibility* of gases is evident. The compression of gases is also exemplified during the compression stroke of the engine. Compressed air is being used on some cars for operating the brakes. Pumps are represented by the compression pump for inflating the tires, by the centrifugal pump for keeping the water circulating through the radiators, and by the oil pump which forces oil to the bearings.

Chap. 4. In a review of this chapter we are reminded of the fact that *moving molecules* exert pressure in the tires and in the cylinders. The impacts of the moving molecules furnish the driving force for the pistons. *Cohesion* is important in the strength of materials, and the sticky varnish or lacquer is an excellent example of *adhesion*. The steel in the springs must have great resiliency, and the air in the tires is one of the best examples of *perfect elasticity*. Light oil is used for lubricating some of the bearings, and heavy grease is used in bearings where the weight of the parts is greater. Oils of lesser *viscosity* are used in winter, since at a lower temperature the viscosity increases.

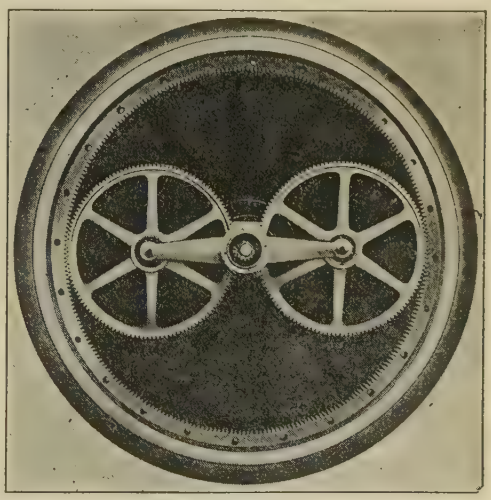


FIG. 764. — Drive wheel with outer disc removed. Drive pinion is supported by teeth of two idler gears, giving efficiency of 97%.

Chap. 5. Without *force* applied to the pistons, no car could run. *Parallel forces* are applied to the steering wheel, furnishing an interesting example of the couple. The student should be able to mention several other applications of parallel forces, or of forces acting at an angle. All the later models of cars are underslung. The frame bends down between the axles and the engine is suspended so low that the *center of gravity* is much lower than in older models. (See Figs. 175 and 176.) Thus greater *stability* is secured. Such increased stability and an increased length in wheel-base both contribute to "roadability," or ease of riding. Fig. 764 shows the balanced gears in a wheel of one type of motor truck. Much attention is paid to the balancing of the crankshaft in an effort to minimize vibration.

Chap. 6. Cars are built for *motion.* Theoretically it is possible for a driver to start with *uniformly accelerated motion* as he applies more force to the accelerator. In stopping a machine, the motion is *retarded;* unfortunately it is not usually *uniformly* retarded. *Newton's Laws of Motion* all apply to the automobile. The pavement reacts against the rear wheels as they push the car forward. Heavy cars traveling at a high velocity are hard to stop, because their *momentum* is equal to the mass times the velocity. Mud flies from the wheels on account of centrifugal force. Too frequently a wrecked car at a curve bears mute testimony to the fact that the driver did not know that high *velocity* and sharp curves both tend to increase centrifugal force. Methods used to

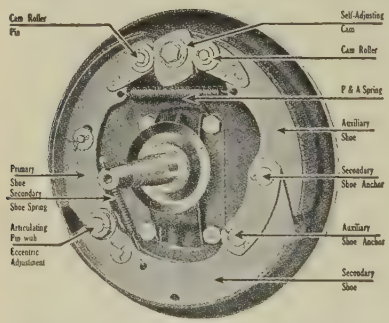


FIG. 765. — As the cam is turned by force applied to the brake pedal, the brake shoes are pushed outward against the brake drum.

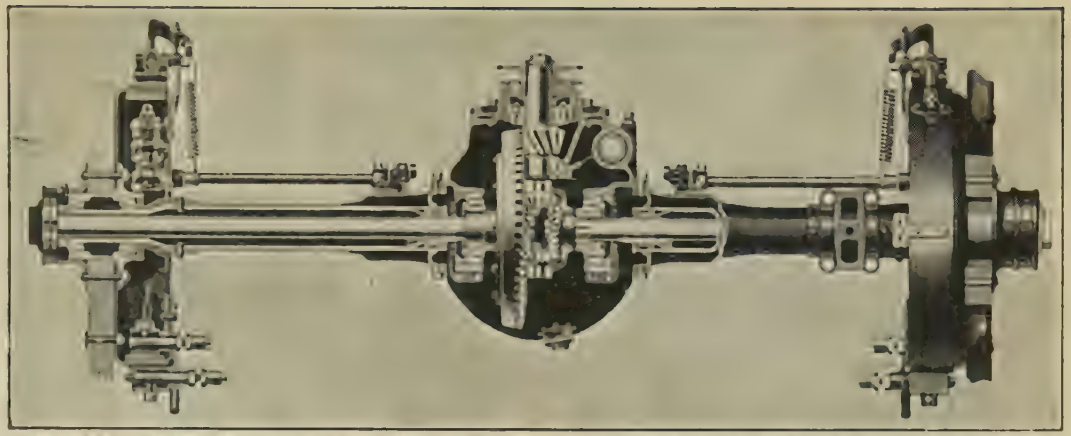


FIG. 766. — Full-floating rear axle and differential. The thrust roller bearings and brake bands are also shown. The foot, or service brake, acts on a flat, circular strip of steel lined with some friction material such as raybestos. When the brake lever is pressed, it pulls this band of steel tightly around a drum attached to the rear wheel, thus using friction to stop the car. The emergency brake lever expands a band of raybestos covered steel against the inner surface of the brake drum.

increase friction follow: 1. Friction material is used on the face of the clutch and for lining the brake bands. (See Fig. 765.) 2. Non-skid tires are used, and non-skid chains for mud or snow. 3. Lock washers prevent loss of nuts by increasing friction. On the other hand, *friction is reduced* by the following methods: 1. Bearings are highly polished. 2. Stream lines reduce air resistance. 3. Ball bearings and roller bearings are used extensively. 4. Oil and grease are used because fluid friction is less than solid friction. Fig. 766 shows a sectional view of a full-floating rear axle. The housing is cut away to show the differential and the bearings. The student should note the free use of ball and roller bearings in all the sectional diagrams of the parts of the automobile. (See Fig. 767.)

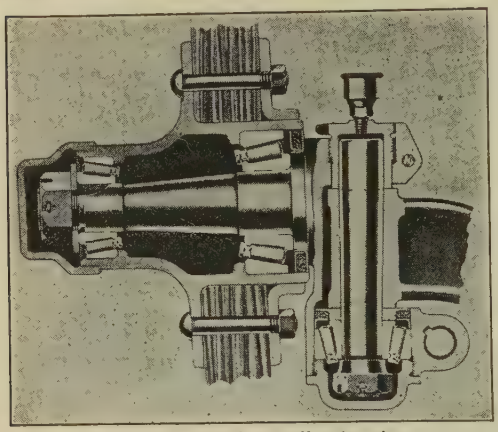


Fig. 767. — Timken roller bearings.

Chap. 7. The work done by a car is measured by the same units that we studied. The salesman tells the prospective purchaser what horse power the engine will develop. The total force applied to a piston multiplied by the length of stroke equals the work done. (Force times distance.) If we know the number of revolutions per second, we can find the horse power by the following formula:

$$\text{H.P.} = \frac{\text{pressure} \times \text{area} \times \text{length} \times \text{number}}{550 \times 2}.$$

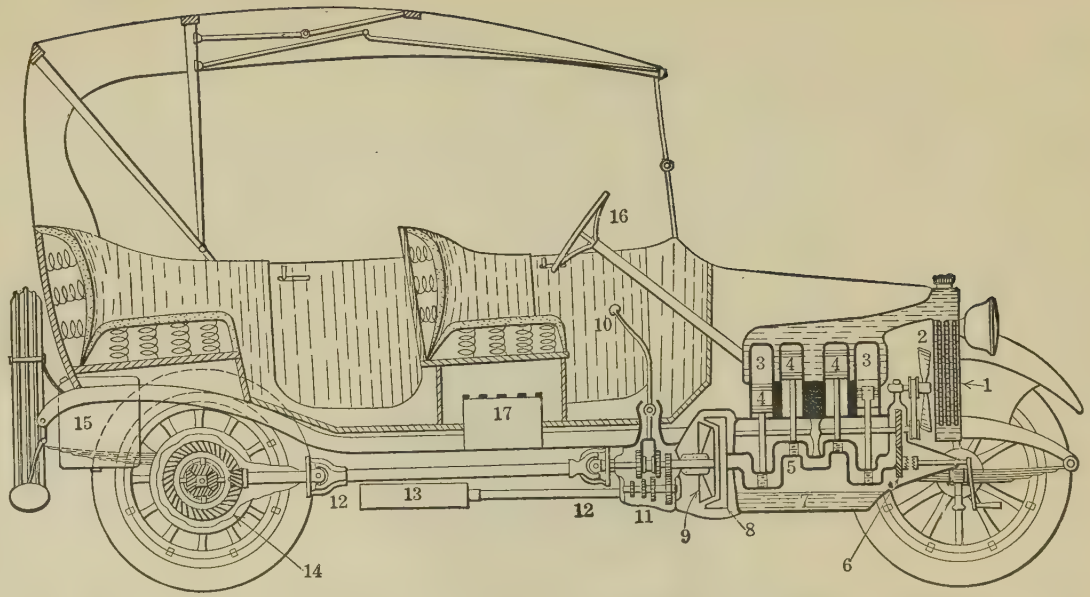


FIG. 768. — Diagram of car in profile. 1, radiator; 2, fan; 3, cylinders; 4, pistons; 5, crank-shaft; 6, timing gears; 7, oil reservoir; 8, flywheel; 9, clutch; 10, gear-shift lever; 11, transmission gears; 12, universal joint; 13, muffler; 14, differential; 15, gasoline tank; 16, steering wheel; 17, battery.

The Society of Automobile Engineers uses the following simple formula to give the indicated horse power:

$$\text{H.P.} = \frac{D^2N}{2.5}.$$

N is the number of cylinders, and D the diameter of each cylinder in inches. Of course this formula is only an approximation, since it does not take into consideration the length of stroke or any variation in compression.

Chap. 8. The automobile is a multiplicity of *machines.* There are levers, screws, cams, and gears in endless number, all working in accord with the general law of machines. The diagram of a car in profile, as shown in Fig. 768, furnishes the student with an idea of the manner in which many simple machines articulate to make a big compound machine. To illustrate, the steering wheel acts on a worm gear which transmits the applied force to the steering knuckle. The front spindle upon which the wheel turns forms one arm of a bent lever steering knuckle, which is pivoted to the front axle by means of a king bolt. The steering wheel and the rear wheels are examples of the *wheel and axle.* The worm drive is used on some motor trucks. (See Fig. 769.)

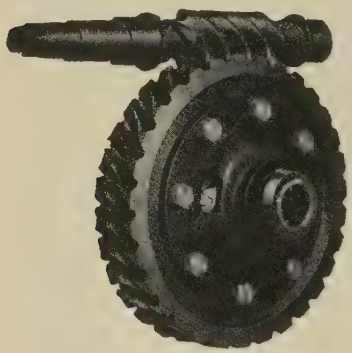


Fig. 769. — Worm drive motor truck.

627. Review of Heat. *Chap. 9.* The moto-meter, a type of thermometer, is being replaced by a temperature indicator on the instrument board. An engine runs better when it is warm, but it should not get too hot. The lining of the brakes may burn, if overheated by friction.

Chap. 10. The cylinders expand when they are heated, and

the pistons must be made of such material that they will expand the same amount. If their expansion is less, there will be a leakage of gas. If the expansion is more, they will "freeze," or become so tight they cannot be moved. Invar is used for certain parts to prevent change of length when the temperature changes. As the temperature of the air in the tires increases, the gas tries to expand. Since it is confined,

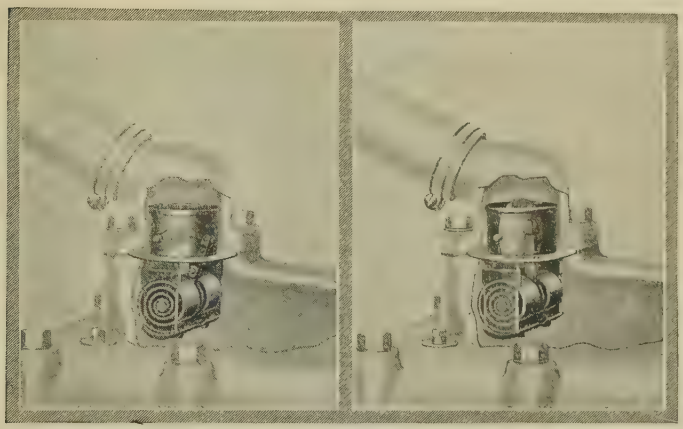


FIG. 770. — Valve at left retards the circulation of the water in the cooling system. As the water becomes hot, the thermostat opens the valve (right).

it will exert more pressure. The heat from the exploding gases in the cylinder causes great expansion and furnishes the driving force for the engine. (Law of Charles.) A thermostat is sometimes used to control the flow of water in the cooling system. (See Fig. 770.)

Chap. 11. The laws of evaporation are applied in the carburetor and in the cooling system. In the winter time fractional distillation of the freezing mixture may result. Solids are sometimes dissolved in the water to lower its freezing point, for a cracked water-jacket or radiator may furnish too convincing a proof of the expansion of freezing

water. Some of these solids are corrosive. Hence a mixture of alcohol and water, of glycerine and water, or of glycerine, alcohol, and water is more often used. A mixture of 30% of alcohol and 70% of water has a freezing point of about $-1°$ F. A more permanent mixture, containing 15% alcohol, 15% glycerine, and 70% water, freezes at $-5°$ F. Glycerine and water are now extensively used, since the glycerine does not evaporate.

Chap. 12. The constant series of explosions in the cylinders would soon heat them red hot if cooling systems were

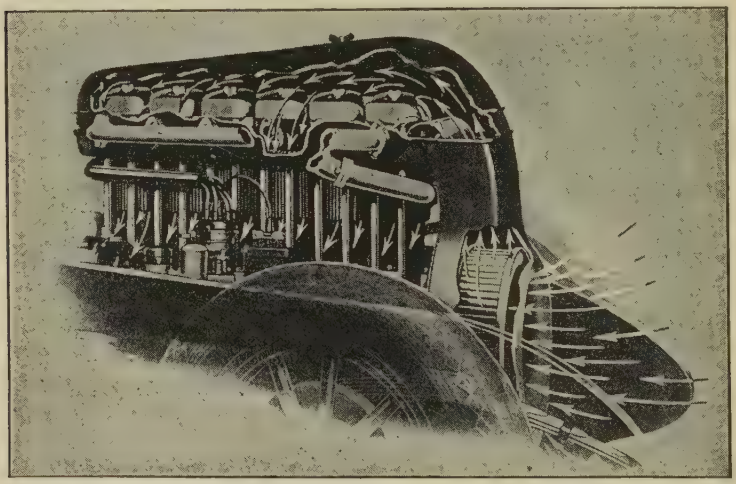


FIG. 771. — A fan pushes the air over and around the cylinders to keep them cool.

not used. Motor-cycle engines and the engines of some cars are air-cooled. In such cases the outside surface of the cylinders is made irregular to increase the amount of surface exposed to the cooling air currents. A powerful fan produces a partial vacuum so that air is pushed around the cylinders to carry away the excess heat. Heat is lost by *conduction*, *convection*, and *radiation*. (See Fig. 771.) The engines of most

cars are water-jacketed. The water, which has a high *thermal capacity*, absorbs heat from the cylinders and then flows to the radiator, where it loses heat to the air that is sucked through the radiator by means of a rapidly rotating fan. In the Thermo-Syphon system of cooling, the water circulates by convection. If the circulation is sluggish, the water may freeze at the bottom of the radiator and boil at the top. To keep the water circulating freely, a centrifugal pump is used in the majority of cars. The heat from the exhaust gases is sometimes utilized to warm the carburetor and also to operate a small heater for the inside of a closed car.

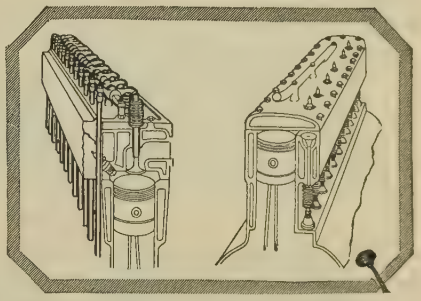


FIG. 772. — Valve-in-head motor (left). An L-head motor is shown at right. Note the position of the valves, push-rods, and spark-plugs in each type.

Chap. 13. This chapter includes the power plant, which has been reviewed to some extent in § 619. Motor cycles use the two-cycle engine. Fig. 772 shows two types of valve control. The one at the left is the valve-in-head motor; the one at the right shows an L-head motor. The student will observe that the valves are pushed upward by means of the cam-shaft. Sleeve valves are used in some cars.

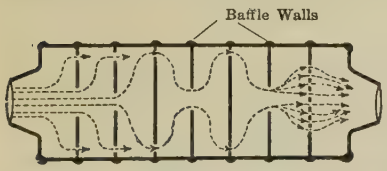


FIG. 773. — Muffler. Exhaust gases take circuitous path.

628. Review of Sound. *Chap. 14.* Machinery seldom runs without vibration, and vibrations set up sound waves. The poppet valves are more noisy than sleeve valves. En-

gines are now cushioned in some cars in an effort to reduce noise. The muffler, Fig. 773, is used on all cars to deaden the noise from the exhaust of the engine. Airplanes do not use a muffler, and the engines are very noisy. The muffler reduces the efficiency of the motor about 1%; hence motorists sometimes cut out the muffler and let the exhaust gases escape directly into the air. In most states, laws forbid the use of the cut-out. Efforts are also made to reduce noises by setting the teeth at an angle in spiral or helical gears. Motorists sometimes locate "knocks" in the engine by holding one end of a screw driver against the cylinder and then resting the side of the head upon the handle of the screw driver. This is an interesting example of the transmission of sound by solids.

Chap. 15. Novelists often speak of a purring motor. A well-oiled motor may run so smoothly that its sound is *musical*, or it may produce irregular vibrations that are *discordant*. The common automobile horn, in which the sound is produced by the rotating armature of an electric motor throwing a diaphragm into vibration, is generally raucous. The siren, which is now used only on fire-trucks, ambulances, and other official cars, is usually more musical.

629. Review of Light. *Chap. 16.* For night driving, artificial light must be used. Nearly all the states regulate by law the maximum *candle power* lamp that may be used. For the headlights, the bulb is generally 21-C.P. Lights that are too bright may produce glare and sharp *shadows*.

Chap. 17. The headlights of an automobile make use of *regular* and *diffused reflection*. If the lamp is placed just a trifle nearer the parabolic reflector than the *principal focus*, the reflected rays will be slightly divergent, as shown in Fig. 774. The effect of placing the lamp at the principal focus is shown in Fig. 775. If the lamp is too far from the principal focus, the light will be reflected as shown in Fig. 776. When the lamp is not centered, the reflected rays will appear as in

Fig. 777. A *plane mirror* to enable the driver to see cars approaching from the rear is now a part of the equipment of nearly every closed car. With such a mirror, the driver can judge distance, but his field is narrow. A convex mirror on the fender serves the same purpose. With such a mirror,

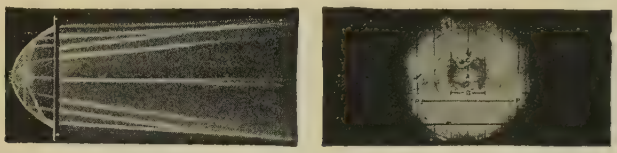


FIG. 774. — Head-light, properly focused. Rays slightly divergent.

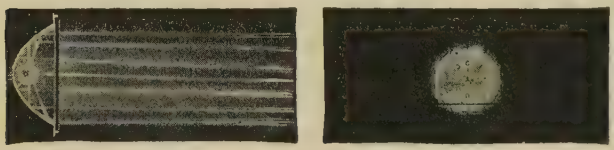


FIG. 775. — When lamp is at principal focus, rays are parallel.

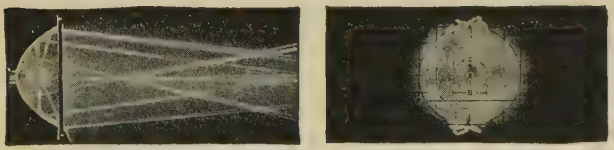


FIG. 776. — Rays are too converging.

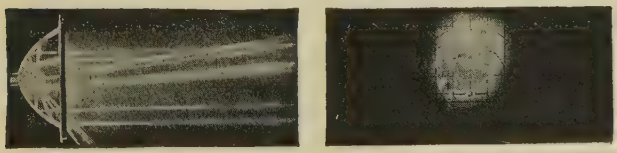


FIG. 777. — Lamp is not centered.

the driver has a wider field of vision, but he cannot judge the distance of the approaching car.

Chap. 18. The state of Massachusetts now requires the owner of a car to have his lights tested periodically. The majority of states have a list of headlight lenses that have

been approved. They are supposed to eliminate "glare." Anti-glare lenses diffuse the light that passes through them, and direct it somewhat downward so that the driver approaching the car from the front is not blinded. (See Fig. 778.) Thus *reflection* and *refraction* play an important part in the automobile.

Fig. 778. — Anti-glare lens.

Chap. 19. The driver of a car can never be very successful until he learns to judge of distance accurately. He is constantly called upon to estimate the distance between his car and the car ahead, or between two cars between which he must pass. Then if he can judge his speed, and the distance within which he can stop, he may be a good driver. During the World War, trucks and other conveyances were camouflaged to promote low visibility.

Chap. 20. For distinction and beauty, *color* is important. The red tail-light is displayed at night as a danger signal. Persons who are color blind cannot obtain a driver's license in the state of New Jersey. When so many traffic lights are flashing green, orange, and red in turn, a driver who cannot tell the difference between red and green is a menace to others.

630. Review of Magnetism and Electricity. *Chap. 21.* In the Ford magneto, there are 16 stationary coils. Sixteen *permanent magnets* are fastened to the flywheel of the engine and thus revolve with it. Thus they produce current for ignition purposes. (See Fig. 779.) Of course a permanent magnet finds use in the ammeter of the car.

Chap. 22. In the copper wires leading to the ignition, lights, etc., we have examples of *conductors.* They are always *insulated,* and in some cars the spark plugs and distributor are water-proofed so that the ignition system will work successfully when deluged with water. The insulation

of the car from the earth by the rubber tires seems to make the automobile immune from lightning.

Chap. 23. If we study the electrical system of a motor car, we find that *Ohm's Law* is applicable, that the *laws of resistance* are used, and that electrical pressure is measured in *volts* and current in *amperes.* The storage cells are connected in *series* to increase the voltage.

Chap. 24. The *electro-magnet* finds use in the horn motor, in the generator, and in the starting motor. An ingenious little trouble lamp has several turns of wire wound on an

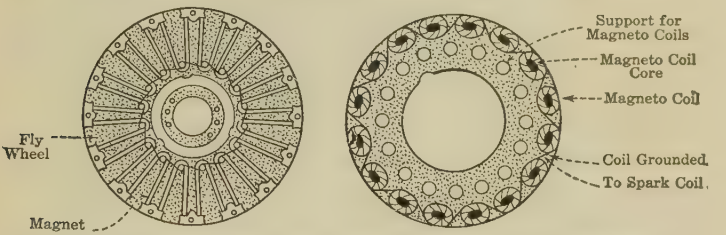


FIG. 779. — In this magneto the magnets rotate with the flywheel. The disc carrying the coils is stationary.

iron core. These coils are in series with the filament. When the lamp is lighted, the core is magnetized and will remain attached to any piece of iron on the frame or body of the car with which it is brought into contact. The *chemical effects* of the electric current are utilized in the charging of the storage battery, in extracting some of the metals for use in the car, and for nickel or chromium plating. The lamps furnish us with a review of the heating and lighting effects of the electric current. The various electrical circuits are fitted with fuses or circuit breakers to take care of an *overload* or a *short circuit.*

Chap. 25. An *ammeter* on the instrument board of the car is used to show when the battery is being charged. In ordinary driving at moderate speed, the ammeter should show a rate of charging of from 10 to 18 amperes. When

the horn is being sounded, the lights are turned on, or the self-starter is in use, the ammeter shows discharge.

Chap. 26. To keep the storage battery fully charged, a *generator* is used. It is usually mounted on the accessory shaft, which is geared with the crank-shaft. An *underload circuit breaker* is used to disconnect the generator from the battery when the car is running too slowly to develop at least the 8-volt pressure needed to charge the battery. Thus the battery cannot discharge back through the generator. If batteries are charged too rapidly they may be injured. Hence an *overload circuit breaker*, or a *relay*, is used to cut out the battery when a car is being driven at a high speed. As the car runs faster, more lines of force are cut per second by the armature; hence the voltage produced by the generator varies with the speed of the car.

A *series-wound motor* is used for the self-starter, because such a motor has a high starting torque. The horn, too, is usually operated by a small electric motor.

Chap. 27. The *induction coil* finds use in the automobile. A six-volt battery will not give high enough pressure to produce a spark between the terminals of the spark plugs. Hence the coil is used to raise the voltage when the circuit is broken by the timer. If a magneto is used for the ignition, then a "make" and "break" is unnecessary, since the current is alternating. With its magnets, conductors, cells, ammeter, motor, generator, lights, and spark coils, the automobile utilizes nearly every principle of magnetism and electricity.

QUESTIONS

1. Is a wheel a lever? Explain.

2. With the ordinary differential, is a chain on one rear wheel a help in starting a car in the snow or on slippery streets? Explain.

3. Refer to Fig. 768 and pick out as many simple machines as you can.

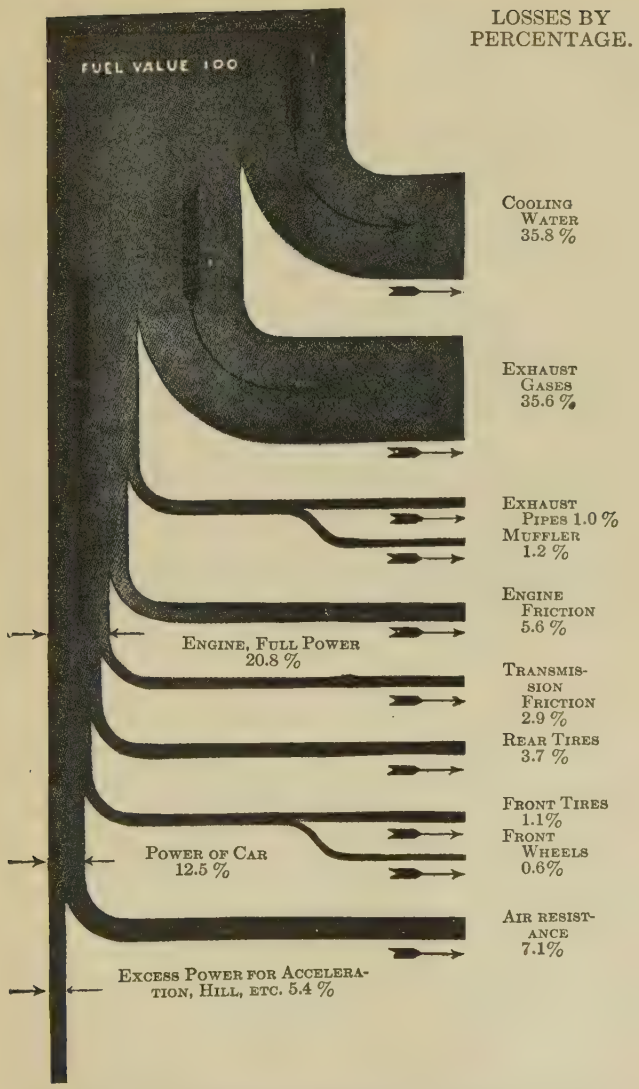

LOSSES BY PERCENTAGE.
FUEL VALUE 100
Cooling Water 35.8 %
Exhaust Gases 35.6 %
Exhaust Pipes 1.0 %
Muffler 1.2 %
Engine Friction 5.6 %
Engine, Full Power 20.8 %
Transmission Friction 2.9 %
Rear Tires 3.7 %
Front Tires 1.1%
Front Wheels 0.6%
Power of Car 12.5 %
Air resistance 7.1%
Excess Power for Acceleration, Hill, etc. 5.4 %

Fig. 780. — Diagram shows dispersion of energy from fuel by a high-class touring car traveling at a speed of 40 miles per hour. (*Courtesy of Tide Water Oil Co.*)

4. Why does a car steer more easily if the steering wheel has a large diameter?

5. Why does increasing the number of cylinders give greater flexibility to a gas engine?

6. Is it possible for a four-cylinder car to have more power than one which has six cylinders? Explain.

7. Why is it necessary to bring a car to a full stop before shifting to reverse gear?

8. Why is it economical to drive a car at moderate speed, but wasteful to drive at a very high speed?

9. It is impossible to start a car if the cylinders are "flooded," or full of gasoline vapor. Explain.

10. Will a car climb a hill more readily if fitted with rear wheels of 30″ or of 34″ diameter? Explain.

11. What is the effect of "advancing" and of "retarding" the spark?

12. Show how inflating a tire exemplifies: (*a*) heat by friction and compression; (*b*) molecular motion; (*c*) the law of Boyle; (*d*) Pascal's law.

13. Is the energy in gasoline kinetic or potential? Discuss the transformations of energy involved in starting and running an automobile. See energy diagram, Fig. 780.

APPENDIX A

ADDITIONAL PROBLEMS

CHAPTER 1

1. An exporter buys 10,000 yd. of cloth in New York at 75¢ a yd. If he sells it in Rio de Janeiro at 90¢ a meter, does he gain or lose by the transaction, and how much?

2. A tank is 8 ft. long, 6 ft. wide, and 4 ft. deep. How many liters of water does it hold? How many grams? How many kilograms?

3. Capt. Arturo Ferrarin and Major Del Prete flew from Rome to Brazil, a distance of 4600 miles. Calculate this distance in kilometers.

4. Excavation is to be made for a cellar 30 ft. long, 24 ft. wide, and 6 ft. deep. If the earthy material to be removed has a density of 125 lb. per cu. ft., how many 5-ton-truck loads of material must be removed?

5. A rectangular tank holds 1000 liters. It is 40 dm. long, and 100 mm. wide. Find its depth in centimeters.

CHAPTER 2

6. A mill dam is 50 ft. long and 20 ft. high. Find the total force of the water against the dam, when the water is 16 ft. deep.

7. A gate 4 ft. long and 2 ft. high is placed in the bottom of a dam where the water is 16 ft. deep. Find the total force against the gate.

8. What is the total force against a gate 4 ft. square at the bottom of the side of a dam, if the bottom of the gate is 22 ft. beneath the surface of the water?

9. Find the pressure in lb. per sq. in. upon a faucet which is 30 ft. above the street main, if the reservoir is 180 ft. above the level of the main.

10. The density of gasoline is 0.7 gm./c.c. Calculate the weight of gasoline in a tank 30 ft. in diameter and 10 ft. deep.

11. The area of the large piston of a hydraulic press is 240 sq. in. What must be the area of the small piston, if an effort of 20 lb. is needed to overcome a resistance of 4800 lb.? If the small piston moves 30 in., how far will the large piston move?

12. If 900 gm. of sulphuric acid, $d = 1.8$ gm./c.c., are poured into a cylinder 4 cm. in diameter, to what height will the acid rise?

13. A cubical box 6 ft. on an edge is placed under water with its upper surface horizontal, and 4 ft. beneath the surface of the water. Find: (a) the total force on one side of the box; (b) the total force downward on the top of the box; (c) the total force upward on the bottom of the box; and, (d) the loss of weight of the box.

14. A glass bottle weighs 31.2 gm. in air and 22 gm. in water. Calculate the density of the glass and the number of c.c. of glass used in making the bottle.

15. A coal barge with vertical sides is 30 ft. long and 20 ft. wide. It rises 2 ft. in sea water when coal is removed. How many tons of coal were removed?

16. A block of wood has a density of 0.6 gm./c.c. and weighs 720 gm. If 300 c.c. of aluminum, $d = 2.7$ gm./c.c., are attached to the block of wood, what will the combination weigh in water? What will it weigh in alcohol, $d = 0.8$ gm./c.c.? What force must be used to submerge it in chloroform, $d = 1.5$ gm./c.c.?

17. A cube of wood floating in water supports a weight of 200 gm. It rises 2 cm. when the weight is removed. Find the size of the cube.

18. A body weighs 200 gm. in air, 120 gm. in water, and 142 gm. in ether. Calculate: (a) the volume of the body; (b) its density; and (c) the density of the ether.

19. As a submarine floats with 0.8 of its volume submerged, it displaces 2400 tons of water. Before the rudders are set for diving, it is desired to have only 0.05 of the volume above the surface. What weight of sea water must be admitted, and how many cu. ft.?

CHAPTER 3

20. What is the pressure of the air in gm. per sq. cm. when the barometer reads 70 cm.? When the barometer reads 60 cm.? When the barometer reads 80 cm.?

21. Assuming the air pressure to be 14.7 lb. per sq. in., to what

total pressure is a diver subjected when he descends to a depth of 200 ft. in sea-water?

22. A bubble of gas has a volume of 0.2 c.c. at the bottom of a lake 90 meters deep. If the bubble rises to the surface, where a water barometer shows a reading of 10 meters, what will be its volume?

23. A bladder containing 3 cu. ft. of air at atmospheric pressure, when the water barometer reads 32 ft., is sunk in water to a depth of 96 ft. Find the volume of the bladder.

24. A two-liter flask weighs 875 gm. It contains 700 c.c. of water. When an unknown liquid is added until the flask is full, the total weight is 3525 gm. Calculate the density of the unknown liquid.

25. A liter flask weighs 345 gm. It is half full of alcohol, density 0.8 gm./c.c., and half full of toluol. The total weight is 1315 gm. Calculate the density of the toluol.

26. The capacity of an automobile tire is 20 liters. How many liters of air must be pumped into the tire to raise the pressure to 44.1 lb. per sq. in., if the original pressure was 14.7 lb. per sq. in.?

27. A balloon has a capacity of 25,000 cu. m. If it is filled with hydrogen gas, which has a weight of 0.09 Kgm. per cu. m., what is the total buoyancy of the hydrogen? The weight of air is 1.29 Kgm. per cu. m. If the total weight of the balloon and contents is 12,000 Kgm., what load can the balloon carry?

28. A balloon has a capacity of 40,000 cu. ft. It is filled with hydrogen which weighs 0.0055 lb. per cu. ft. The balloon, rigging, and basket weigh 1000 lb., and the two passengers 150 lb. each. If the weight of 1 cu. ft. of air is 0.078 lb., how much force will be needed to keep the balloon from rising?

CHAPTER 5

29. A boy weighing 80 lb. hangs from the center of a clothes line, causing the two parts of the line to make a right angle with each other. What is the pull on each part of the line?

30. In dragging a sled, a boy pulls with a force of 75 lb.; his hand is 15 in. higher than the sled at the point where the rope is attached. What is the effective force used in pulling the sled forward, if the rope is 60 in. long?

31. A girl pushes against the handle of a vacuum cleaner with a force of 15 lb. If the handle makes an angle of 45° with the floor, what is the effective force which pushes the cleaner forward?

32. A bar 10 ft. long is free to turn on an axis 6 ft. from the end A. At this end a force of 40 lb. acts at right angles to the bar; what force must be applied at the other end at B, if the force acts at an angle of 60° with the bar?

33. A ladder 24 ft. long weighs 220 lb. Its C. of G. is 8 ft. from the end A. The ladder is held horizontally by ropes 1 ft. from each end. If a painter who weighs 154 lb. stands 3 ft. from A, find what weight each rope supports.

CHAPTER 6

34. A sled goes down a hill 400 ft. long in 10 sec. What is its acceleration? How far did it travel the first second? With what velocity was it moving at the end of the tenth second?

35. A ball rolling down an inclined plane with uniformly accelerated motion moves 4 ft. the first second. Find: (a) its acceleration; (b) the length of the incline, if it takes 20 sec. for the ball to reach the bottom; and (c) its velocity at the end of the twentieth second.

36. A ball thrown over a tree was in the air 6 sec. What is the height of the tree? With what velocity was the ball thrown upward?

37. An automobile starting from rest accelerates to 30 mi. per hr. in 10 sec. Find: (a) the acceleration in ft. per sec.; (b) the distance the car traveled in the 10 sec.

38. A car has a velocity of 30 ft. per sec. If the retardation of the brakes is 5 ft. per sec., in what distance can the car be stopped? What is the shortest distance in which the car can be stopped, if the velocity of the car when the brakes are applied is 60 ft. per sec.?

39. Calculate the momentum of a 4000-lb. car traveling 30 mi. per hr.

40. A coaster going down hill travels 45 ft. during the fifth second. Find his acceleration. How far does he travel in 20 sec.? What will his velocity be at the end of the 20th sec.?

CHAPTER 7

41. What H.P. will be developed by a turbine which uses 10,000 cu. ft. of water per sec., if the water head is 143 ft.?

42. A forge hammer weighs 484 lb. and rises once each sec. to a height of 3 ft. What H.P. engine is needed to operate it?

43. What is the backward thrust of the propeller of a 400-H.P. engine when an airplane is being driven by it at a velocity of 90 mi. per hr.?

44. How long a time will be needed for a 100-H.P. engine working at an efficiency of 100% to pump 10,000 cu. ft. of water to a height of 363 ft.? How long a time will be needed if the efficiency is only 80%?

45. A boat moving 30 mi. per hr. overcomes a constant resistance of 400 lb. What H.P. engine, working at an efficiency of 75%, will be needed?

CHAPTER 8

46. A uniform rod 10 ft. long has weights of 12 and 20 lb. suspended from the ends. Neglecting the weight of the rod, at what point will it balance? 6.25'

47. A bar 9 ft. long supports at its ends weights of 20 and 25 lb. At what point is the fulcrum? 5'

48. A pole 12 ft. long projects horizontally from a wall. It will just break if a weight of 20 lb. is hung from its end. How far out on the pole may an 80-lb. boy venture with safety? 3'

49. A uniform bar 2 ft. long weighs 5 lb. A weight of 1 lb. is hung from the end A. How far from this end will the combination balance? 5/6'

50. How much work is done in pushing a 2-ton safe across a floor a distance of 40 ft., if the coefficient of friction is 0.1? How long should it take 2 men to do it? 203#

51. A 16-ft. plank used as a see-saw weighs 80 lb. It balances 10 ft. from one end when a 50-lb. girl is seated 1 ft. from that end and a boy is seated at the other end. Calculate the weight of the boy. 101.7#

52. A lever 18 ft. long weighs 200 lb. The center of gravity is 7 ft. from the larger end, at which a stone weighing 2050 lb. is placed.

The fulcrum is 12 in. from the stone. What force at the opposite end of the lever is needed to secure equilibrium? 50

53. A motor having a speed of 1200 revolutions per min. runs a sewing machine at the rate of 400 revolutions per min. If the diameter of the pulley on the motor is 1.5 in., what is the diameter of the pulley on the sewing machine? 4 1/2

54. It is found that 63,000 ft. lb. of work are done by a derrick in lifting a weight of 1800 lb. to a height of 30 ft. What is its efficiency? 55.5

55. A system of four fixed and three movable pulleys is used to pull a weight of 2100 lb. up a plank 15 ft. long. If one end of the plank is 3 ft. higher than the other end, what effort will be needed? What effort will be required if the pulley system has an efficiency of $66\frac{2}{3}\%$ and the plane an efficiency of 90%? 100

56. If an effort of 20 lb. moves through a circumference of 10 ft., and lifts a weight of 3000 lb., what is the pitch of the screw, assuming the efficiency is 25%? .2"

CHAPTER 10

57. A copper shingle is 10 in. square. How much will it increase in area if it is heated from −20° C. to 30° C.? Consider the coefficient of superficial expansion as double that of the linear coefficient.

58. A gas has a volume of 450 c.c. when the temperature is 14° F. and the pressure is 50 in. of mercury. What pressure is needed to keep the volume constant, if the temperature is reduced to −30° C.?

59. A 30-ft. steam-pipe expands 0.0195 when heated from 0° C. to 50° C. Calculate its coefficient of linear expansion.

60. A cubical block of iron is 10 cm. on a side when the temperature is 0° C. Find its volume when the temperature rises to 1000° C.

CHAPTER 11

61. When 100 gm. of iron at a temperature of 200° C. are dropped into 300 gm. of oil, the temperature of the oil rises from 10° C. to 20° C. Find the sp. ht. of the oil.

62. 300 gm. of a metal which has a sp. ht. of 0.22 are taken from steam at 100° C. and placed on a block of ice; 83 gm. of ice are

melted as the metal cools to zero. Calculate the heat of fusion of ice.

63. A sample of coal yields 13,500 B.T.U.'s per lb. How many lb. of coal must be burned to convert 100 lb. of water at 32° F. into steam at 212° F., assuming that 40% of the fuel value is lost by radiation?

64. A radiator weighs 300 lb. How many lb. of steam at 212° F. will be needed to heat the radiator from 52° F. to 212° F.?

65. How many B.T.U.'s will be needed to melt 100 lb. of ice, and to warm the resulting water to 212° F.?

66. A pitcher weighing 4 lb. contains 4 lb. of water at 50° F. If the sp. ht. of the pitcher is 0.2, how many lb. of ice will be needed to cool the water and pitcher to 10° F.?

CHAPTER 14

67. A sound produced at the bottom of a boat is returned after 0.4 sec. How deep is the water?

68. The temperature of the air is 15° C. What length open pipe will be needed to produce resonance with a note whose frequency is 280?

69. When the temperature is 15° C. a projectile having a velocity of 2240 ft. per sec. is heard by the gunner to strike the target in 6 sec. How far away is the target?

70. A man drops a stone into a well and hears it strike the bottom in 5 sec. If sound has a velocity of 1120 ft. per sec., how deep is the well? (Use 32 ft. for g.)

CHAPTER 15

71. If we double the length of a wire, double its diameter, multiply its tension and its density by four, how will its vibration rate be affected?

72. One string is 75 cm. long, 0.25 mm. in diameter, density 7.6 gm. per c.c., and it is stretched by a force of 9 Kgm. Compare its frequency with that of a second string, which is 100 cm. long, 0.5 mm. in diameter, density 8.8 gm. per c.c., and stretched by a force of 25 Kgm.

73. Calculate the lengths of a series of closed pipes that will

produce resonance with the notes in the octave from C to C′ when the temperature is 15° C.

74. A string 30 in. long sounds the note C. Where must it be stopped to produce the notes D, E, and F, successively?

CHAPTER 16

75. A man holds a pencil 6 in. long just 10 in. from his eye. He finds that the ends of the pencil appear to coincide with the top and bottom of a tree which is just 120 ft. distant. How tall is the tree?

76. In a certain library 200-candle-power lamps are suspended 6 ft. from the reading tables. How many foot-candles of light does a reader receive? How many foot-candles will he receive if the lamps are lowered 1 ft.?

77. A light 2 ft. from a book gives 5 foot-candles. How far away must a lamp 25 times as bright be placed to give the same number of foot-candles?

CHAPTER 17

78. A concave mirror has a radius of 12 in. A man 6 ft. tall stands at a distance of 12 ft. from the mirror. Calculate the height of his image. How tall will his image be when he is 6 ft. from the mirror? When he is 9 in. distant? When he is 4 in. distant?

79. An object 6 in. tall is 8 in. in front of a convex mirror of 9 in. focal length. Calculate the distance of the image from the mirror and the height of the image. (Remember that for convex mirrors both $1/D_i$ and $1/F$ are negative.)

80. An object is 15 in. from a mirror and the image is 30 in. from the same side of the mirror. Find the focal length of the mirror. Is the mirror concave or convex?

CHAPTER 23

81. Calculate the lengths of No. 20 manganin wire that would be needed to have resistances of 0.1, 0.2, 0.3, and 0.4 ohm respectively. ($K = 400$.)

82. How many feet of No. 20 manganin wire will be needed to make resistance coils of 10 and 20 ohms respectively?

83. Three cells are connected in series. Each has an E.M.F. of 2 volts and an internal resistance of 0.2 ohm. Three similar cells are connected in series and then the two groups are joined in parallel with an external resistance of 0.3 ohm. What current will flow through the external resistance?

84. The cells of Prob. 83 are grouped as follows: The three groups of two cells in series are wired in parallel and connected to an external resistance of 0.3 ohm. What current will flow?

85. Not more than 0.5 ampere of current is to be used with a motor operating on a 110-volt circuit. If the motor has a resistance of 1 ohm, what resistance must be connected in series with it to cut the current down to 0.5 ampere? Select one kind of wire and its gauge number, and calculate the number of feet of the wire you select that must be used.

CHAPTER 24

86. A percolator, which operates on a 110-volt circuit, uses 5 amperes of current. How long will it take this percolator to heat 1000 gm. of water from 20° C. to 100° C.?

87. How long would it take the percolator described in No. 86 to heat 1000 gm. of water from 20° C. to 100° C., if we substitute for the heating unit a coil whose resistance is only 20 ohms?

88. Joule found that amperes squared $\times$ ohms $\times$ times in seconds must be multiplied by 0.24 to find heating effect in calories. Calculate the constant that would have to be used to find the heat developed in B.T.U.'s.

89. Compare the heating effects developed by a 110-volt circuit when the resistance is 110 ohms with those produced when the resistance is 1 ohm.

90. A heater operates on a 110-volt circuit. An ammeter in series with the heater shows a reading of 5.2 amperes when the current is first turned on, and the temperature of the coil is 20° C. When the temperature rises to 1420° C., the ammeter shows a reading of 4.8 amperes. Calculate the resistance of the heating coil at each temperature and also the temperature coefficient, or resistance change per degree change in temperature.

91. In an electrolytic cell 20 gm. of silver are deposited on the

cathode by a current that flows for 75 minutes. What is the strength of the current in amperes?

92. In a silver-plating bath the current used is 0.2 ampere. How long must a tablespoon be kept in such a bath to have deposited upon it 1 pennyweight (24 grains) of silver?

CHAPTER 25

93. A lamp having a resistance of 45 ohms is joined in series with a coil of 10 ohms across a 220-volt circuit. What is the total resistance of the lamp and the coil? What current will flow through each one of them?

94. If two lamps, having resistances of 55 and 220 ohms respectively, are connected in parallel across the terminals of a 110-volt circuit, what is the current flowing through each lamp? How much current will flow in the main circuit? What is the total resistance of the lamps?

95. Three resistances, 200, 200, and 40 ohms respectively, are connected in series across a 110-volt circuit. What current will flow through these resistances?

96. The three resistances of No. 95 are connected in parallel across a 110-volt circuit. What current will flow through each resistance? What current will flow in the main circuit? Calculate the joint resistance of the three conductors.

97. What voltage is needed to send 9 amperes of current through a parallel circuit if the resistances of the two branches are 4 and 12 ohms respectively?

98. The two branches of a shunt circuit have resistances of 10 and 30 ohms. If the current in the main circuit is 12 amperes, what current will flow in each branch? What voltage must be used?

99. A quarter-horsepower motor, a 660-watt heater and a flatiron using 5 amps. are all connected in parallel on a 110-volt circuit. How many amperes of current do they use? Find cost of operating the three for one hour at 9¢ per kilowatt-hour.

100. Find the efficiency of a 5-H.P. motor that uses 20 amperes of current on a 220-volt circuit.

101. Eight lamps are connected, 2 in series, and in 4 parallel groups, on a 240-volt circuit. If each lamp requires 1 ampere of current, what is the resistance of each lamp? Of the eight lamps?

APPENDIX B

FORMULAS

1. *Density.*

$$D = \frac{W}{V}.$$

D is density; W, weight; and V, volume.

2. *Liquid Pressure.*

$$P = hd.$$

P is pressure; h, the depth of the liquid; and d, the density.

3. *Total Force.*

$$F = ahd.$$

a is the area of the surface; h, depth of liquid; and d, the density.

4. *Boyle's Law.*

$$VP = V'P'.$$

V is original volume; P, original pressure; V', new volume; and P', new pressure.

5. *Accelerated Motion.*

$$V = at, \text{ or } V = gt.$$

V is velocity at end of any given second; t, time; a, acceleration; and g, acceleration when body is freely falling.

6. *Accelerated Motion.*

$$S = \tfrac{1}{2}at^2, \text{ or } S = \tfrac{1}{2}gt^2.$$

S is distance for any given number of seconds; t, time; a, acceleration; and g, acceleration due to gravity.

7. *Accelerated Motion.*

$$S' = \tfrac{1}{2}a(2t-1), \text{ or } S' = \tfrac{1}{2}g(2t-1).$$

S' is the distance the body moves in any *given* second; t, time; a, acceleration; and g, acceleration when body is freely falling.

8. *Accelerated Motion.*

$$V = \sqrt{2aS}, \text{ or } V = \sqrt{2gS}.$$

V is velocity at end of any given second; S, distance; a, acceleration; and g, acceleration due to gravity.

9. *Pendulum. Law of Lengths.*

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

t and t' represent the times of vibration; l and l' represent the lengths of the pendulums.

10. *Pendulum.*

$$t = \pi\sqrt{\frac{l}{g}}.$$

t represents time; l, length of pendulum; and g, acceleration due to gravity.

11. *Centrifugal Force.*

$$\text{C.F.} = \frac{mv^2}{gr}.$$

If m represents mass in grams, v, velocity in centimeters, r, radius in cm., and g, acceleration due to gravity, then C.F. equals the centrifugal force in grams.

When m = lb., v and r, ft., then C.F. equals centrifugal force in pounds.

12. *Work.*

$$W = Fs.$$

W represents work done; F, acting force; and s, the distance the force acts.

13. *Power.*

$$\text{H.P.} = \frac{Fs}{550t}.$$

If F represents force in pounds, s, distance in feet, and t the time in seconds, then H.P. represents horse power.

14. *Potential Energy.*

$$\text{P.E. (in gravitational units)} = mh.$$

m is mass and h the distance.

$$\text{P.E. (in ergs)} = mgh.$$

15. *Kinetic Energy.*

$$\text{K.E. (in ergs)} = \tfrac{1}{2}mv^2.$$

m is mass in gm., and v the velocity in centimeters.

16. *Work Principle.*

$$E \times d = R \times d'.$$

E is effort; d, distance effort moves; R, resistance; and d', distance resistance moves.

17. *Lever.*

$$\text{M.A.} = \frac{EF}{RF}.$$

EF is length of effort arm and RF the length of the resistance arm. *M.A.* is mechanical advantage of force; the advantage of speed in machines is always the inverse ratio of the mechanical advantage of force.

18. *Pulley.*

$$En = R.$$

E is effort; R, the resistance; and n, the number of strands supporting the movable block.

19. *Wheel and Axle.*

$$\text{M.A.} = \frac{C}{c} \text{ or } \frac{D}{d} \text{ or } \frac{R}{r}.$$

C, D, and R represent respectively the circumference, diameter, or radius of the wheel; c, d, and r represent respectively the circumference, diameter, or radius of the axle.

20. *Inclined Plane.*

$$\text{M.A.} = \frac{l}{h}.$$

l represents the length of the plane and h the height. (Force is applied parallel to plane.)

$$\text{M.A.} = \frac{b}{h}.$$

When force is applied parallel to the base of the plane, then b represents the base and h the height.

21. *Screw.*

$$\text{M.A.} = \frac{2\pi r}{d}.$$

r is radius of lever upon which the effort acts, and d is the interval or distance between the threads of the screw.

22. *Centigrade and Fahrenheit Scales.*

$$\frac{C}{F-32} = \frac{5}{9}.$$

C and F represent Centigrade and Fahrenheit thermometer readings.

23. *Laws of Boyle and Charles.*

$$\frac{PV}{T} = \frac{P'V'}{T'}.$$

P, V, and T represent original pressure, volume, and absolute temperature; P', V', and T' represent new pressure, volume, and absolute temperature.

24. *Coefficient of Linear Expansion.*

$$K = \frac{l'-l}{l(t'-t)}.$$

l represents the length before expansion; l', the length after expansion; t, the original temperature; and t', the final temperature.

25. *Heat Exchange.*

$$mst = m's't'.$$

m, s, and t represent the mass, specific heat, and change of temperature in Centigrade degrees of substance losing heat; m', s', and t' represent the mass, specific heat, and change of temperature of substance gaining heat.

26. *Wave length.*

$$v = nl.$$

v is velocity of sound; n, the number of vibrations per second; and l, the wave length.

27. *Size of Object and Image.*

$$S_o : S_i = D_o : D_i.$$

S_o and S_i represent the size of object and image respectively; D_o and D_i represent the distances of object and image from the mirror or lens.

28. *Lens Formula.*

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}.$$

D_o is the object's distance; D_i, the image distance; and F, the focal length.

29. *Ohm's Law.*

$$I = \frac{E}{R}, \text{ or } I = \frac{V}{R}, \text{ or } I = \frac{P.D.}{R}.$$

I is the strength of current in amperes; R, the resistance in ohms; E, the electromotive force; V, the voltage; and $P.D.$, the potential difference.

30. *Resistance.*

$$R = \frac{Kl}{d^2}.$$

K is a constant dependent upon the material; l is the length in feet; and d is the diameter of the conductor in mils, or thousandths of an inch.

31. *Cell Formula.*

$$I = \frac{E}{r_i + R_e}.$$

I is the strength of the current; E, the voltage; r_i, the internal resistance of the cell; and R_e, the external resistance.

32. *Series Grouping.*

$$I = \frac{nE}{nr_i + R_e}.$$

I is the strength of the current; E, the voltage; r_i, the internal resistance of a single cell; R_e, the total external resistance; and n, the number of cells.

33. *Parallel Grouping.*

$$I = \frac{E}{\frac{r_i}{n} + R_e}.$$

The letters have the same significance as in No. 32.

34. *Electric Heating.*

$$\text{Calories} = I^2R \times t \times 0.24.$$

I is the strength of the current in amperes; R, the resistance; and t, the time in seconds.

35. *Shunt Resistance.*

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}, \text{ or } R = \frac{rr'}{r + r'}.$$

R represents total resistance; r, the resistance of one branch of the shunt; and r' the resistance of the other branch.

APPENDIX C

TABLE 1. — USEFUL NUMBERS

12 in.	= 1 ft.	3 ft.	= 1 yd.
$16\frac{1}{2}$ ft.	= 1 rd.	320 rd.	= 1 mi.
5280 ft.	= 1 mi.	144 sq. in.	= 1 sq. ft.
9 sq. ft.	= 1 sq. yd.	1728 cu. in.	= 1 cu. ft.
27 cu. ft.	= 1 cu. yd.	2150.4 cu. in.	= 1 bu.
231 cu. in.	= 1 gal.	60 mi. per hr.	= 88 ft. per sec.
1 lb. avoir.	= 7000 gr.	1 lb. Troy	= 5760 gr.
1 oz. avoir.	= 437.5 gr.	1 oz. Troy	= 480 gr.
1 cu. ft. of water weighs 62.4 lb.		π^2	= 9.86965.
Circumference of a circle	$= 2\pi r$	Area of circle	$= \pi r^2$, or $\frac{1}{4}\ \pi d^2$
Surface of sphere	$= 4\pi r^2$	Volume of sphere	$= \frac{1}{6}\ \pi d^3$

TABLE 2. — METRIC–ENGLISH EQUIVALENTS

1 in.	= 2.5399 cm.	1 ft.	= 30.479 cm.
1 mi.	= 1609.3 m.	1 mi.	= 1.6093 Km.
1 mm.	= .03937 in.	1 cm.	= .3937 in.
1 m.	= 39.3708 in.	1 m.	= 3.2809 ft.
1 m.	= 1.0936 yd.	1 sq. cm.	= 0.155 sq. in.
1 sq. in.	= 6.451 sq. cm.	1 cu. in.	= 16.3862 c. c.
1 lb.	= 453.593 gm.	1 Kgm.	= 2.2046 lb.
1 oz.	= 28.3495 gm.	1 gm.	= 15.432 gr.

TABLE 3. — SPECIFIC WEIGHT OF SOLIDS

Aluminum	2.7	Coal, bituminous	1.26–1.4
Antimony	6.72	Copper	8.9
Beeswax	0.96	Cork	0.24
Brass	8.2–8.7	Diamond	3.53
Brick	1.6–2.0	Elm	0.58
Bronze	8.7	Glass, crown	2.5
Butter	0.94	Glass, flint	3.0–3.6
Carbon	1.7–3.5	Gold	19.3
Chestnut	0.61	Gold, 18k.	14.88
Cherry	0.71	Granite	2.65
Coal, anthracite	1.26–1.8	Graphite	2.50

TABLE 3. — *Continued.*

Human Body	1.07	Paraffin	0.824–0.94
Ice	0.917	Pine	0.46–0.55
Iron, cast	7.1–7.6	Platinum	21.4
Iron, steel	7.79	Porcelain	2.38
Iron, wrought	7.8–7.9	Quartz	2.65
Lead	11.34	Silver	10.5
Lignum vitae	1.33	Silver, sterling	10.38
Limestone	3.18	Sulphur	2.0
Maple	0.755	Tallow	0.94
Magnesium	1.74	Tin	7.0–7.3
Marble	2.7	Tungsten	18.7
Oak	0.85	Zinc	7.1

TABLE 4. — SPECIFIC WEIGHT OF LIQUIDS

Alcohol, grain	0.794	Mercury	13.56
Alcohol, wood	0.804	Milk	1.029
Carbon bisulphide	1.27	Nitric acid, 68%	1.41
Carbon tetrachloride	1.60	Oil, castor	0.963
Chloroform	1.50	Oil, cottonseed	0.924
Ether	0.72	Oil, linseed	0.94
Gasoline	0.68–0.71	Oil, olive	0.916
Glycerin	1.26	Turpentine	0.87
Hydrochloric acid	1.20	Sulphuric acid	1.84
Kerosene	0.778–0.804	Water, sea	1.026

TABLE 5. — CAPACITY OF AIR IN GRAINS OF WATER VAPOR PER CUBIC FOOT

Degrees F.	Grains per Cubic Foot	Degrees F.	Grains per Cubic Foot	Degrees F.	Grains per Cubic Foot	Degrees F.	Grains per Cubic Foot
10	.776	46	3.539	66	7.009	86	13.127
20	1.235	48	3.800	68	7.480	88	13.937
30	1.935	50	4.076	70	7.980	90	14.790
32	2.133	52	4.372	72	8.508	92	15.689
34	2.279	54	4.685	74	9.066	94	16.634
36	2.457	56	5.016	76	9.655	96	17.626
38	2.646	58	5.370	78	10.277	98	18.671
40	2.849	60	5.745	80	10.934	100	19.766
42	3.064	62	6.142	82	11.626	102	20.917
44	3.294	64	6.563	84	12.356	104	22.125

TABLE 6. — HEAT CONSTANTS

Name	Specific Heat	Melting Point	Boiling Point	Heat of Fusion	Heat of Vaporization
Alcohol	.65	−130° C.	78° C.		205
Aluminum	.217	657	2200	76.8	
Ammonia		−75	−33.5	108	295
Brass	.09	912			
Copper	.093	1065	2310	42	
Glass	.198				
Ice	.5	0		80	
Iron	.113	1550	2450	28	
Lead	.031	327	1525	5.8	
Mercury	.033	−39	357	2.8	
Platinum	.0323	1760		27.2	
Silver	.056	961	1952	21.	
Tungsten	.0336	3000			
Steam	.48				
Water	1.00		100		536
Zinc	.093	419	918	28	

TABLE 7. — TENSILE STRENGTH

Material	Pounds per Square Inch	Material	Pounds per Square Inch
Aluminum	30,030–40,000	Iron, piano wire	357,000–390,000
Brass	50,000–150,000	Lead, drawn	2600–3300
Bronze wire phosphor	110,000–140,000	Platinum, drawn	50,000
Copper, drawn	60,000–70,000	Silver, drawn	42,000
Iron, annealed	50,000–60,000	Steel, ordinary	80,000–330,000
Iron, hard drawn	80,000–120,000	Steel, maximum	460,000

TABLE 8. — VELOCITY OF SOUND IN VARIOUS MEDIA (APPROXIMATE)

Material	Feet per Second	Material	Feet per Second
Air	1,089	Iron	16,500
Aluminum	16,750	Steel	16,500
Brass	11,500	Water, 4° C.	4,590
Copper	12,000	Water, 15° C.	4,615
Glass	16,500	Wood, along grain	14,300
Hydrogen	4,163	Wood, across grain	12,600

TABLE 9. — VAPOR PRESSURE OF WATER IN MILLIMETERS OF MERCURY

Degrees C.	Millimeters	Degrees C.	Millimeters	Degrees C.	Millimeters
0	4.5	23	20.9	60	148.9
5	6.5	24	22.2	70	233.3
10	9.1	25	23.5	80	354.7
15	12.7	26	25.0	85	433.1
16	13.5	27	26.5	90	525.4
17	14.4	28	28.1	95	633.7
18	15.3	29	29.8	96	657.7
19	16.3	30	31.5	97	682.1
20	17.3	35	41.6	98	707.3
21	18.5	40	54.8	99	733.2
22	19.6	50	92.0	100	760.

TABLE 10. — DENSITY OF WATER AT VARYING TEMPERATURES

Degrees C.	Grams per Cubic Centimeter	Degrees C.	Grams per Cubic Centimeter	Degrees C.	Grams per Cubic Centimeter
0	.99987	15	.99913	60	.98324
1	.99993	20	.99823	65	.98059
2	.99997	25	.99708	70	.97781
3	.99999	30	.99568	75	.97489
4	1.00000	35	.99406	80	.97183
5	.99999	40	.99225	85	.96865
6	.99998	45	.99025	90	.96534
8	.99987	50	.98807	95	.96192
10	.99973	55	.98573	100	.95838

TABLE 11. — RELATIVE CONDUCTIVITY OF HEAT

Silver 100	German silver . 7–8	Magnesia . . .016
Copper 92	Mercury . . 1.6	Paper 013
Aluminum . . . 48	Concrete . . .22	Sawdust 012
Zinc 27	Glass 11–.23	Wool 010
Brass 21–28	Sand, white . .09	Silk 0095
Platinum . . . 17	Asbestos . . .04	Felt 0087
Iron 12–15	Soil, dry . . .033	Air 005
Steel 6–11.7	Firebrick . . .028	Cotton wool . .0043
Lead 8	Linen 021	

TABLE 12. — PROPERTIES OF COPPER WIRE

Gauge Number	Diameter, mils	Ohms per 1000 Feet at 0° C.	Ohms per 1000 Feet at 20° C.	Feet per Ohm 20° C.
0000	460	.04516	.04901	20,400
000	409.6	.05695	.06180	16,180
00	364.8	.07181	.07793	12,830
0	324.9	.09055	.09827	10,180
1	289.3	.1142	.1239	8,070
2	257.6	.1440	.1563	6,400
3	229.4	.1816	.1970	5,075
4	204.3	.2289	.2485	4,025
5	181.9	.2887	.3133	3,192
6	162.0	.3640	.3951	2,531
7	144.3	.4590	.4982	2,007
8	128.5	.5988	.6282	1,592
9	114.4	.7299	.7921	1,262
10	101.9	.9203	.9989	1,001
11	90.74	1.161	1.260	794.0
12	80.81	1.463	1.588	629.6
13	71.96	1.845	2.003	499.3
14	64.08	2.327	2.525	396.0
15	57.07	2.934	3.184	314.0
16	50.82	3.700	4.016	249.0
17	45.26	4.666	5.064	197.5
18	40.30	5.883	6.385	156.6
19	35.89	7.418	8.051	124.2
20	31.96	9.355	10.15	98.5
21	28.45	11.80	12.80	78.11
22	25.35	14.87	16.14	61.95
23	22.57	18.76	20.36	49.13
24	20.10	23.65	25.67	38.96
25	17.90	29.82	32.37	30.90
26	15.94	37.61	40.81	24.50
27	14.20	47.42	51.47	19.43
28	12.64	59.80	64.90	15.41
29	11.26	75.40	81.83	12.22
30	10.03	95.08	103.2	9.691
31	8.928	119.9	130.1	7.685
32	7.950	151.2	164.1	6.095
33	7.080	190.6	206.9	4.833
34	6.305	240.4	260.9	3.833
35	5.615	303.1	329.0	3.040
36	5.000	382.2	414.8	2.411
37	4.453	482.0	523.1	1.912
38	3.965	607.8	659.6	1.516
39	3.531	766.4	831.8	1.202
40	3.145	966.5	1049	0.953

TABLE 13. — HYGROMETRY

Dry Thermometer, ° F.	Difference between Dry and Wet-bulb Thermometers														
	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°
50	93	87	81	74	68	62	56	50	44	39	33	28	22	17	12
52	94	88	81	75	69	63	58	52	46	41	36	30	25	20	15
54	94	88	82	76	70	65	59	54	48	43	38	33	28	23	18
56	94	88	82	77	71	66	61	55	50	45	40	35	31	26	21
58	94	89	83	77	72	67	62	57	52	47	42	38	33	28	24
60	94	89	84	78	73	68	63	58	53	49	44	40	35	31	27
62	94	89	84	79	74	69	64	60	55	50	46	41	37	33	29
64	95	90	85	79	75	70	66	61	56	52	48	43	39	35	31
66	95	90	85	80	76	71	66	62	58	53	49	45	41	37	33
68	95	90	85	81	76	72	67	63	59	55	51	47	43	39	35
70	95	90	86	81	77	72	68	64	60	56	52	48	44	40	37
72	95	91	86	82	78	73	69	65	61	57	53	49	46	42	39
74	95	91	86	82	78	74	70	66	62	58	54	51	47	44	40
76	96	91	87	83	78	74	70	67	63	59	55	52	48	45	42
78	96	91	87	83	79	75	71	67	64	60	57	53	50	46	43
80	96	91	87	83	79	76	72	68	64	61	57	54	51	47	44
84	96	92	88	84	80	77	73	70	66	63	59	56	53	50	47
88	96	92	88	85	81	78	74	71	67	64	61	58	55	52	49
90	96	92	89	85	82	78	75	72	68	64	62	58	56	53	50

TABLE 14. — NATURAL SINES AND TANGENTS

Angle	Sine	Tangent	Angle	Sine	Tangent	Angle	Sine	Tangent
0	0.000	0.000	31	0.515	0.601	62	0.883	1.881
1	0.017	0.017	32	0.530	0.625	63	0.891	1.963
2	0.035	0.035	33	0.545	0.649	64	0.899	2.050
3	0.052	0.052	34	0.559	0.675	65	0.906	2.145
4	0.070	0.070	35	0.574	0.700	66	0.914	2.246
5	0.087	0.087	36	0.588	0.727	67	0.921	2.356
6	0.105	0.105	37	0.602	0.754	68	0.927	2.475
7	0.122	0.123	38	0.616	0.781	69	0.934	2.605
8	0.139	0.141	39	0.629	0.810	70	0.940	2.747
9	0.156	0.158	40	0.643	0.839	71	0.946	2.904
10	0.174	0.176	41	0.656	0.869	72	0.951	3.078
11	0.191	0.194	42	0.669	0.900	73	0.956	3.271
12	0.208	0.213	43	0.682	0.933	74	0.961	3.487
13	0.225	0.231	44	0.695	0.966	75	0.966	3.732
14	0.242	0.249	45	0.707	1.000	76	0.970	4.011
15	0.259	0.268	46	0.719	1.036	77	0.974	4.331
16	0.276	0.287	47	0.731	1.072	78	0.978	4.705
17	0.292	0.306	48	0.743	1.111	79	0.982	5.145
18	0.309	0.325	49	0.755	1.150	80	0.985	5.671
19	0.326	0.344	50	0.766	1.192	81	0.988	6.314
20	0.342	0.364	51	0.777	1.235	82	0.990	7.115
21	0.358	0.384	52	0.788	1.280	83	0.993	8.144
22	0.375	0.404	53	0.799	1.327	84	0.995	9.514
23	0.391	0.424	54	0.809	1.376	85	0.996	11.43
24	0.407	0.445	55	0.819	1.428	86	0.998	14.30
25	0.423	0.466	56	0.829	1.483	87	0.999	19.08
26	0.438	0.488	57	0.839	1.540	88	0.999	28.64
27	0.454	0.510	58	0.848	1.600	89	1.000	57.29
28	0.469	0.532	59	0.857	1.664	90	1.000	Infinity
29	0.485	0.554	60	0.866	1.732			
30	0.500	0.577	61	0.875	1.804			

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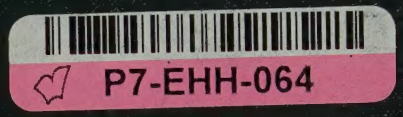
	V , S	$a = \frac{V^2}{2S}$
V	A (g) , T	$V = aT$ $V =$
	S , A (g)	$V = \sqrt{2AS}$ or $\sqrt{2g}$
		$V^2 = 2gS$
T	V, A	$T = \frac{V}{A}$
	S, A	$T = \sqrt{\frac{2S}{A}}$
h or S	V, T	$S = \frac{VT}{2}$
	a, T	$S = \frac{1}{2} a T^2$
	V, A	$S = \frac{V^2}{2a}$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